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OPERATION OF AUTOMATIC ANTICORROSION DEVICES

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ABSTRACT

This book considers the protection of metallic underground structures from corrosion, as well as the operation of highly effective protection systems. A brief description is presented of existing automatic anticorrosion devices. Special attention is paid to the description of basic circuit components of these devices. Proglems of maintenance, adjustment, and testing of protective units and of the individual subassemblies of these units are analyzed in detail. Also included are servicing methods of automatic electrodraining systems and cathode stations.

The book is intended for specialists dealing with operation, maintenance and adjustment of protective systems.

S Y M B O L S

used in the text and in circuit diagrams

I	current
U	voltage
$U_{вх}$	input voltage
$U_{вых}$	output voltage
$U_{у}$	control voltage
C	capacitors
R	resistors
T	transistors
Д, D	diodes
Д, В, в	rectifiers
Д, ДУ, DУ	thyristors
Д, ст	stabistors
ТР	transformers
УМ, МА	magnetic amplifiers
УПТ	DC amplifiers
П, ВК	switches
ПР	fuses
ПК, ВК	toggle switches
ДН, ДР	chokes
$L_{ф}$	inductance
$C_{ф}$	capacitance
ШР	plug connectors
КП	push-botton switches
ЛО, ЛС	indicator lights

INTRODUCTION

A wide scope of industrial and housing construction in the USSR is inseparably linked with increasing lengths of underground pipelines and communication lines. The Five-Year Plan for development of the national economy of the USSR during 1971-1975 envisages further increases in construction of underground pipelines for gas, oil and petroleum products. Increased volume of the pipeline transportation requires reliable protection from soil corrosion, especially the corrosion produced by stray currents from electrified rail systems.

Efficient protective methods, which are used in zones of underground structures characterized by stable anodes and polarization, are based on a protective potential, the average value of which is selected in such a way as to make these zones cathode stable. Experience accumulated on the corrosion protection of underground structures in cities makes it possible to select rational means of electroprotection. Based on the analytic results of corrosion measurements, draining devices are installed, as a rule, at points where underground structures are very close to the return feeder cables of tramway or railroad rails. The peripheral sections of pipelines and cables located in stray current zones or in aggressive soil media are protected by cathodic devices.

The specific feature of existing protection systems is the ability to produce variable potentials within the stray current zones to compensate variations in the rail traction loads. Designers of electrical anticorrosion devices seek to design units that produce average potentials which will be higher than the maximum amplitude of positive pulses produced by the stray current field. In other words, the most unfavorable conditions (such as a maximum intensity of stray currents in a given area) are taken as guiding points during selection of the parameters of polarization units, powered draining devices, and cathode stations not equipped with automatic control. Adjustment of powered draining devices and cathode stations to the highest possible load of the traction network results in their optimum performance during a limited time when the traffic intensity of the electrified railroad or tramway (which are the sources of stray currents) reaches its peak hours. Even within this comparatively short time, which does not exceed 10-15% of

24 hours, sharp variations in the traction loads are always present. These loads determine, in turn, the potential variations on the underground structures. The performance of unregulated protective devices during the remaining hours is therefore characterized by considerable deviations from optimum values of applied potentials.

Sharp drops in the traction load responsible for an excessive applied potential on an underground structure is not only damaging to the structure but also results in a waste of energy used by active anticorrosion devices. Experience with powered draining units connected to the rails of tramways and railroads [1] show that 50% of the electrical energy is wasted when a 2 kW voltage booster was used. Variations in potentials on underground structures could be much higher with nonautomatic cathode stations operating in the stray current zones.

The main purpose for the use of automatic protective devices is to prolong the service life of underground structures. Trouble-free performance of these structures is obtained by maintaining an optimum potential on them. First, this excludes damage produced by corrosion, and secondly, favorable conditions are created for preserving the dielectric properties of insulating coatings.

It should be noted that the design of automatic protective units differ markedly from that of conventioanl electric draining devices and cathodic stations. Automatic adjustment of the protective potential on underground structures requires the use of thyristors, transistors, resistors, capacitors and other components. Reliable operation of an automatic protective unit can be achieved by careful circuit adjustment and proper performance of its components.

The broad application of new automatic anticorrosion devices and their proper use results in a further increase of economical and technological benefits.

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CHAPTER 1

TYPES OF AUTOMATIC PROTECTIVE DEVICES

The electrochemical protection of underground structures is one of the most effective methods for the prevention of corrosion damage. According to "Rules on Protection of Underground Metal Structures from Corrosion" (SN 266-63), all underground communication lines located in zones with aggressive soil or stray currents should be protected not only by strong anti-corrosive coatings but also by cathodic polarization.

Presently three types of devices for cathodic polarization are known. They differ by the method of supplying the current necessary for securing the protective potential on the underground structure. First, passive draining systems protect underground structures by changing the current distribution in the rail - ground - underground structure system. Second, cathode stations which use AC lines or independent sources of current. Third, simple protectors which form galvanic cells with the metal of the underground structure.

Passive draining devices connect underground structures to networks of electrified railroads or tramways. Their design is based on semiconducting or relay-switching circuits with one-way conductivity. Simplicity in design and performance reliability of polarized draining systems has resulted in their broad use. A noticeable redistribution of currents and potentials in the rail - ground - underground structure system is the specific characteristic of protective draining systems. When electric draining devices are used, rail potentials decrease by some absolute value, and new draining devices in a given region are not needed. With the development of a system of anticorrosion protection of underground structures, the application and effectiveness of passive draining systems decrease.

The importance of polarized draining devices and their contribution to a total volume of anticorrosion protection is insignificant in large cities with well developed protective systems. The so-called "deep draining" method, i.e., connecting draining devices to negative terminals of railway substations, lost its importance because of the replacement of rheostatic control of the potentials on rails by voltage boosters. As a result, the need for powered draining systems and cathode stations grew in importance.

The use of powered draining devices is one of the principal approaches to the increase of efficiency of draining systems. The basic advantage of powered draining devices (as compared with conventional) is the possibility of increasing the draining current by including the additional e.m.f. into the draining device network. This made possible the control of potentials on underground structures over wide ranges.

In many cases the use of powered draining systems provides the only effective protection for underground structures from stray currents. This is true, for example, for an underground structure located within several sources of stray currents when the draining of one of these sources by a rail system is insufficient, or when underground structures have many branches and the polarized drainages can protect only limited sections of these structures.

Use of powered draining systems is economical because it does not require many draining cables and the resulting installation cost is low. This is especially true for underground structures located at a great distance from the rail network. Experimental use of powered draining systems showed that their harmful effect on communication lines is much lower, as compared with cathode stations.

Two approaches can be applied, in principle, to automatically control protective units. In the first case the required potential is changed in relation to the known value of protective current. An automatic device changes this value according to a schedule which considers the seasonal variations of the corrosion state of protected structure, i.e., does not measure the potential value on the structure.

Automatic and self-regulating devices based on the potential value of the underground structure are much more effective. In this case, the potential on the structure is measured continuously by a reference electrode. When a deviation from the established value occurs, an appropriate signal is sent to the actuating unit via an intermediate amplifying unit. Since the automatic anticorrosion system is equipped with feedback, it is possible to readjust its starting parameters to a new required value.

Practically all automatic self-regulating protective devices in stray current zones use the difference in potentials between the underground structure and soil as the controlling signal.

Automatic draining devices UD-AKKh and DUT-AKKh, designed by the Academy of Municipal Economy, are presently in serial production.

The automatic powered draining device UD-AKKh is intended for a surface installation. It performs normally at +35 to -40°C and 85% air humidity. The device is characterized by the following features:

Nominal power output	2 kW
Nominal input voltage	220 VAC
Output voltage control range	0 - 6 VDC
Nominal value of the rectified current	150/300A
Range of the automatically maintained protective potential at a nominal load (with the use of steel reference electrodes)	0.3 - 1.5 V
Accuracy in the maintaining of protective potential on underground structure	±50 mV
Unit size	1000 x 660 x 400 mm
Unit weight	200 kg

Figure 1 presents the functional scheme of the powered electric draining unit UD-AKKh.

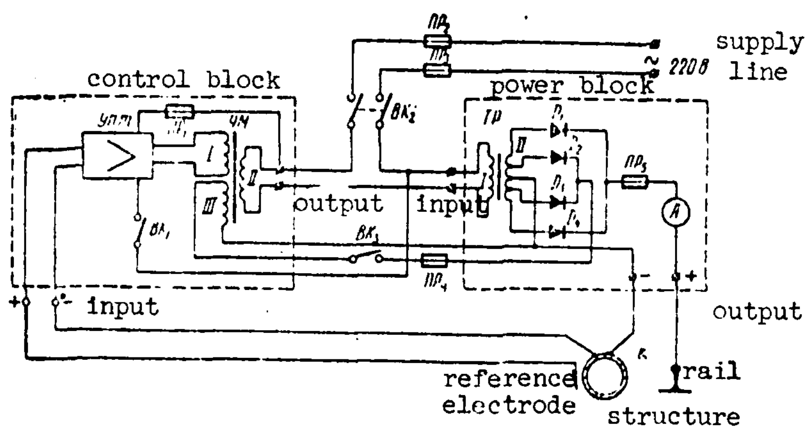


Figure 1. Functional diagram of an automatic powered electric draining unit type UD-AKKh.

The electric draining unit consists of two main subassemblies: control unit and current rectifier. The unit is supplied with power from a 50 Hz, 220 VAC line. The voltage is supplied to two-pole rotary switch BK_2 through safety fuses ΠP_2 and ΠP_3. The one-pole switch BK_1 and safety fuse ΠP_1 are located in the supply circuit of the control unit. The power unit contains step-down transformer TP and two full-wave rectifiers, D_1 - D_4 and D_2 - D_3. The rectified output is connected in series with a draining cable between the protected structure and a rail. Automatic maintenance of the electric potential on the underground structure is secured by a control unit which regulates the output voltage of the power rectifier which feeds the draining network. The control unit is a transistor-magnetic amplifier chain consisting of a transistor DC preamplifier, УПТ, and magnetic output amplifier, УМ.

An error signal produced by a difference in potential between the underground structure and the reference electrode is applied to the input of Y T, which is characterized by a transconductance of 8 - 10 A/V. The output current of Y T drives the control winding of УМ I. An increasing current in winding I of УМ causes a decrease in the inductive reactance in winding (II) of УМ which is connected in series with the primary wirding (I) of the power transformer TP and the single-phase 220 VAC buss. Voltage in the secondary winding (II) of TP and at the rectifier output (which feeds the draining network) increases, and by so doing the correct protective potential on the structure is restored.

In order to increase the efficiency of the whole draining unit when operating with the output current exceeding 150 A, both functional subassemblies are connected by an additional positive feedback network. It consists of feedback winding УМ III and the current-supplying small power rectifier (diodes D_2 and D_3). They are connected to taps on the secondary winding II of TP. The switch BK_3 turns off the feedback network when the unit operates with medium or small currents. The safety fuse ΠP_4 protects this circuit from overloading. When the switch BK_3 is closed, a current appears in the feedback circuit which causes an additional magnetization of the УМ core. Reactance of the operating coil II of УМ decreases further and produces a current increase at the output of the secondary winding of the power transformer TP which feeds rectifiers D_1 and D_4.

Thus current in the draining protection lines increases until the required level is attained or the power of the entire unit is realized (upon the complete saturation of the УМ core).

The automatic draining unit is enclosed in a steel cabinet (Figure 2), the design of which permits attachments of the draining cables (70 - 120 mm^2 in cross section) and the power supply line (220 VAC, 50 Hertz). The front cabinet door is provided with a lock.

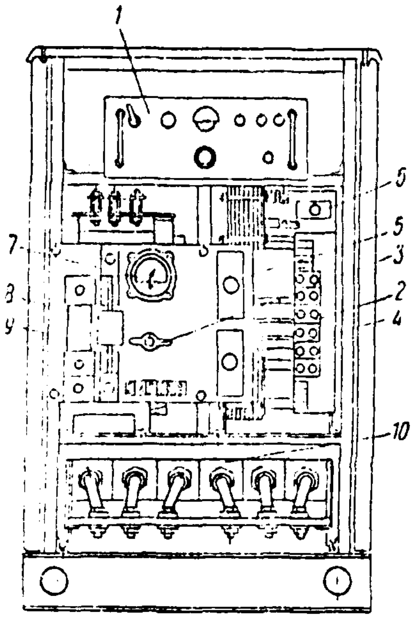


Figure 2. Automatic draining unit type UD-AKKh (location of subassemblies)

There is a welded frame made of angle iron inside the cabinet. A removable module (1), the transistor amplifier, УПТ is installed in the upper part of the frame, which is equipped with a plug connector. The central part of the frame contains the magnetic amplifier and the power transformer TP. Two-pole rotary switch BK_2 (3), safety fuses ΠP_2 - ΠP_5 (4-6 and 8), control ammeter (7) for DC with a 300 A display scale, and the ammeter shunt (9) are also mounted in the central part of the frame. The BK-200 silicon rectifiers (10) are mounted in the lower corners of the frame.

The automatic draining unit DUT-AKKh has the following technical characteristics:

Nominal power output	2 kW
Nominal input voltage	200 VAC
Output voltage control range	0-6-12 V
Nominal value of the output current	150/300 A
Range of the automatically maintained protective potential at a nominal value	0.3 - 1.5 V
Accuracy in the maintaining of protective potential on underground structure	±25 mV
Unit size	1000 x 660 x 400 mm
Unit weight	160 kg

Figure 3 shows the functional scheme of this automatic powered electrodraining unit DUT-AKKh.

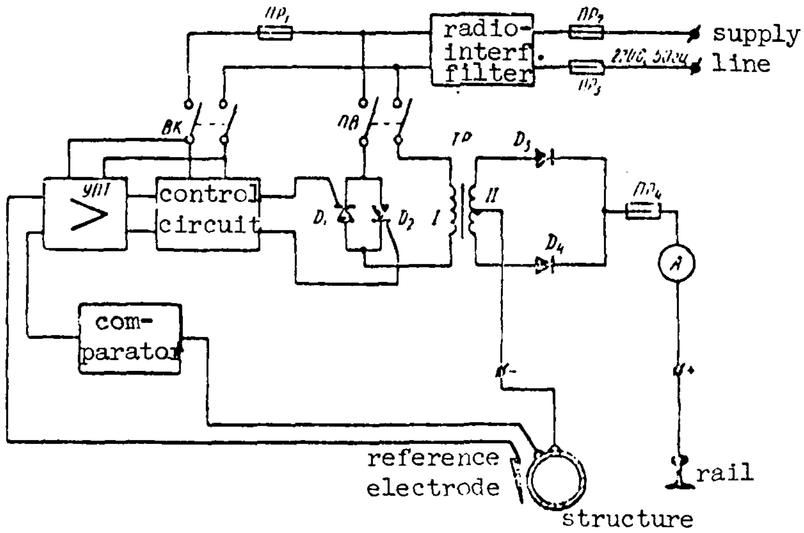


Figure 3. Functional diagram of automatic draining unit type DUT-AKKh.

The use of silicon controlled rectifiers (thyristors D_1 and D_2) is the distinguishing characteristic of this unit. This design makes it possible to exclude the bulky magnetic amplifier, decrease sluggishness of the control

circuit, and increase considerably the accuracy in maintaining the protective potential on underground structures.

The unit is supplied with 220 VAC, 50 hertz from a single-phase line. The supply line is equipped with safety fuses ΠP_1 -ΠP_3, rotary switch ΠB and power switch BK to the control unit. A special protective filter is provided for elimination of radio interference. The power rectifier is full-wave circuit with a midpoint on silicon rectifiers D_3 and D_4. The positive output is connected to a rail through safety fuse ΠP_4, and the negative output (midpoint of the winding II of the transformer TP) to the protected structure. The DC ammeter measures the current in the protective circuit.

Two thyristors D_1 and D_2 serve as controlling elements. They are connected antiparallel with each other and are in series with primary winding I of the power transformer, TP. The semiconductor device for controlling the conduction angle of thyristors D_1 and D_2 is designed to produce continuous control of the output voltage from 0 to nominal.

The control assembly of the unit includes transistorized DC amplifier УПТ the reference circuit and the thyristors control circuit. A signal from the reference electrode is received at the УПТ input and is compared with a reference voltage which is obtained from a stabilized rectifier. The amplified error signal is delivered to the thyristor control circuit. Depending on the error signal, the duration of the control pulses received at the output of the control circuit changes. The output stages are transistor switches which are transformer coupled to the control electrodes of thyristors D_1 and D_2. The pulse-width control method produces reliable performance of the thyristor rectifier, i.e., the conduction angle of thyristors D_1 and D_2 can change continuously from 0 to 180°.

The automatic protection device Model DUT-AKKh is assembled in a cabinet identical to Model UD-AKKh (Figure 4). Exclusion of the magnetic amplifier from the design of this system made it possible to have a special section for the control apparatus (for example, a recording mV meter, type N-373 or N-39). A removable electronic unit (1) with plug connector is installed in the upper part of the welded frame. A light bulb (2) is located above this unit. The following measuring instruments are located below the unit (1): DC ammeter (4), electric supply meter (3), and DC voltmeter (5).

The power transformer (6) is mounted inside the frame. Circuit safety fuses (7) and rotary switch (10) are located below the electric supply meter. An opening for an automatic recorder is located in the right-hand side of the frame and is provided with a plexiglass cover (9).

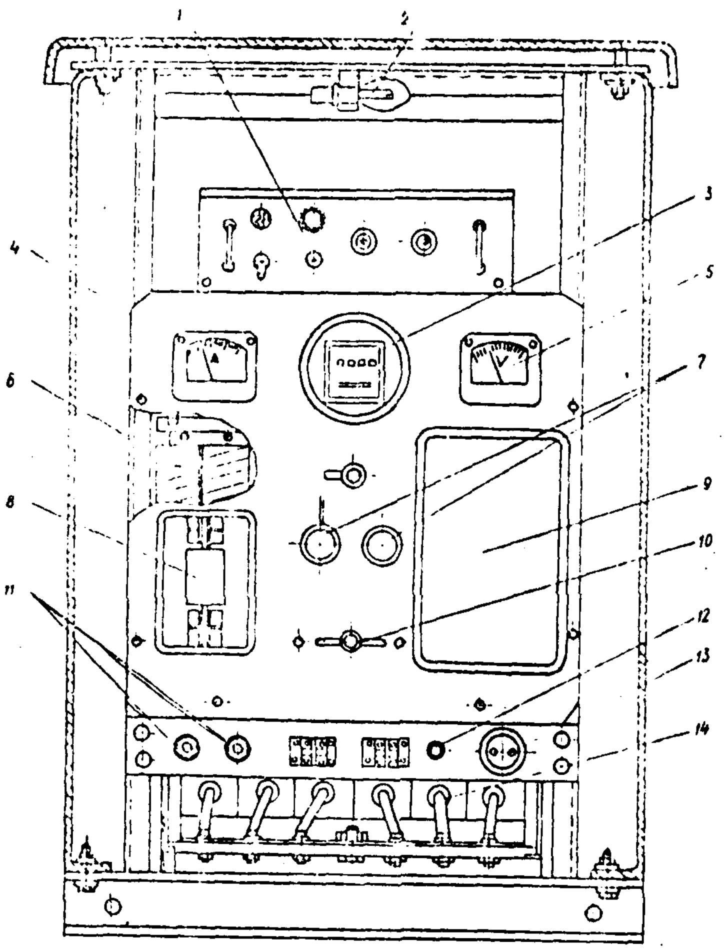


Figure 4. Automatic draining unit type DUT-AKKh

(location of subassemblies)

A safety fuse (8) in the DC circuit is located in the left-hand side of the frame. In the lower part of the frame there is a mounting plate with terminals, (11) for connecting the power supply line and terminal block for a signal circuit. Socket (13) and safety fuse (12) are located nearby. Power rectifier (14) are mounted in lower corners of the frame.

The automatic cathode station AKS-AKKh is designed for protection of city gas, water, heat and power supply lines. The station maintains a needed potential on underground metal structures and has the following characteristics:

Current supply line	220 VAC
Nominal power output	3.5 kW
Protective potential range	0.3 - 1.5 V ± 10%
Output voltage	100/50 V
Output current	35/70 A
Weight	100 kg

Figure 5 shows the functional scheme of the cathodic protection station AKS-AKKh.

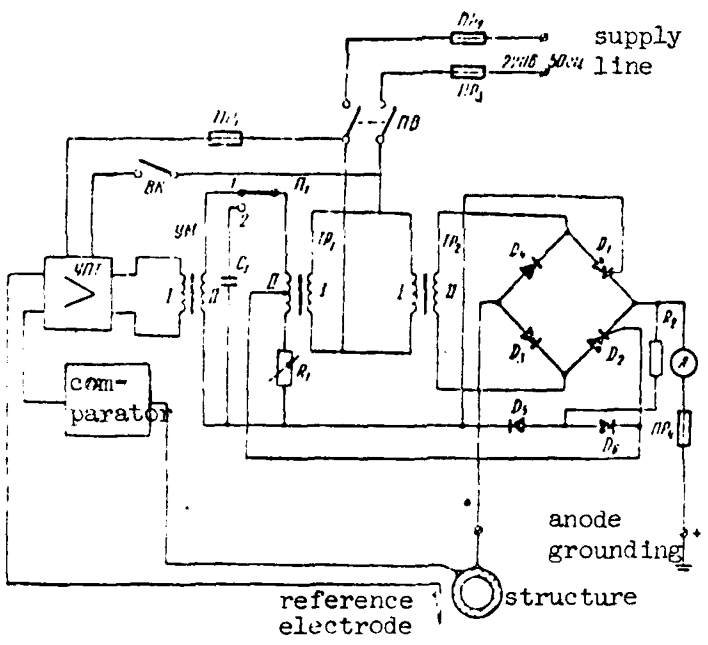


Figure 5. Functional diagram of automatic cathode station type AKS-AKKh

The station is supplied with 220 VAC at 50 Hz from a single-phase network through safety fuses ΠP_2 and ΠP_3 and rotary switch ΠB. The power rectifier is a bridge circuit and with silicon rectifiers D_3 and D_4 and two thyristors D_1 and D_2 perform the rectifying and control functions. The

rectifiers are connected to the secondary winding of the power transformer, TP_2. The output current meter (A) and safety fuse ΠP_4 are located at the rectifier output.

Thyristors D_1 and D_2 are controlled by a phase-shifting bridge network driven by a magnetic amplifier that provides a variable inductance based on a saturated core circuit.

The sinusoidal voltage phase is controlled in this device by changing the inductance or the active resistance in one of the bridge arms. The circuit consists of a step-down transformer TP_1 with the center tap from the winding II, resistor R_1 and the winding II of magnetic amplifier УМ. By changing the magnetization value in winding I of УМ, it is possible to control the inductance in winding II of УМ over a wide range. This produces the phase shift between voltages acting at the bridge diagonals from 0 to 180°. If the magnetic circuit of УМ is saturated, the shift between these voltages approaches zero. In the absence of magnetization the angle approaches 180°. Thus it is possible to continuously control the rectified voltage of the power rectifier D_1 and D_2. Because the controlling electrodes of thyristors D_1 and D_2 are supplied with an alternating voltage of the same frequency as the potentials of their anodes, D_1 and D_2 will conduct only when the voltage applied to their controlling electrodes is positive with respect to thyristor cathodes. Changing the phase of controlling voltage by adjusting the resistance of the variable resistor R_1 or the inductance of УМ II, it is possible to force the current to flow through thyristors D_1 and D_2 during any fraction of a complete half-period. The voltage at the bridge output is proportional to current passing through the rectifiers and is identical in form. Thus, the voltage value in the cathodic protection circuit can be lowered to the required level when the phase shift between the control electrode and the cathodes of thyristors D_1 and D_2 increases from 0 to 180°.

When the switch Π_1 is shifted from the position 1 to position 2, capacitor C_1 is connected to winding II of TP_1 instead of the winding II of УМ. In this case the phase-shifting circuit is transformed into a RC bridge in which the phase controlling the sinusoidal voltage is achieved by changing the resistance of the variable resistor, R_1 thus providing manual control of the output voltage of the station.

The control windings of I provides the collector load for the output stage of УПТ The input signal of УПТ is produced by the reference electrode and protected structure. The reference circuit forms the error signal which determines the value of current in the winding of УМ I, as well as the value of the rectified output voltage.

The automatic cathodic protection station Model AKS-AKKh is mounted on a frame in a standard steel removable cabinet. Removable assemblies (1) and (4, of the phase-shifting device and of the transistorized DC amplifier are located in the upper part of the frame (Figure 6). The input voltage

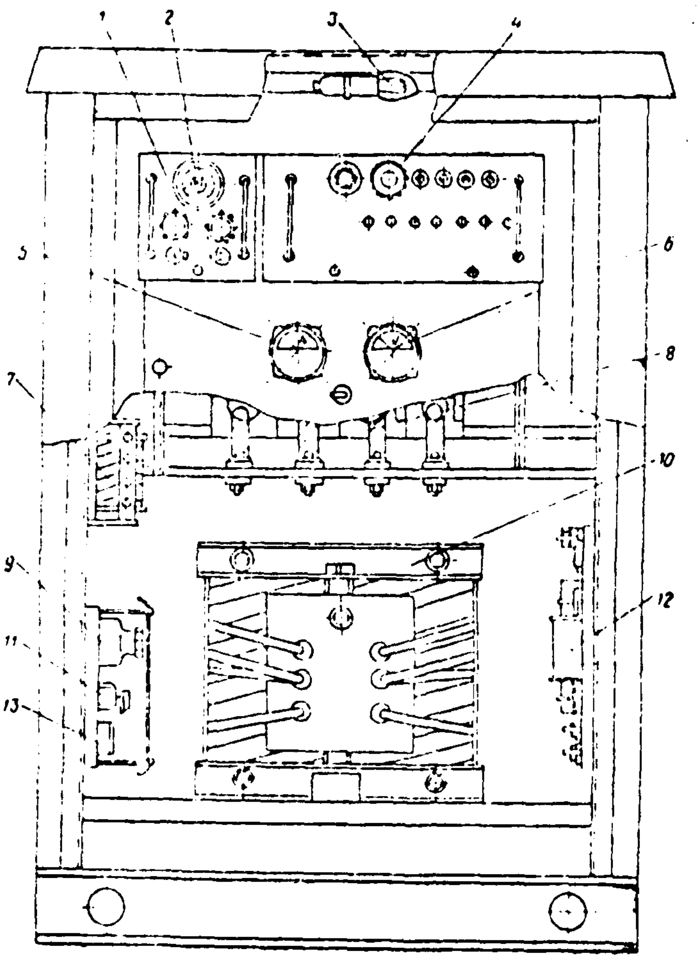


Figure 6. Automatic cathode station type AKS-AKKh

(location of subassemblies)

controller (2) is located in assembly (1). These assemblies are provided with plug-in connectors and can be removed when needed. The illumination bulb LO 3 is located in the upper part of the frame. DC ammeter (5) and voltmeter (6) are installed in the central part of the front panel. Silicon rectifiers BK-200 and thyristors ВКДУ150 (8) are located behind the front panel. The magnetic amplifier УМ1П-15-15-11 (7) is located at the left-hand side of (8). The power transformer (10) with terminal block for the ends of the secondary windings for different output voltage is located in the lower part of the frame. At the left-hand side, the AC power panel with safety fuses (9), rotary switch (11) and plug receptacle (13) is mounted. The safety fuse (12) for DC circuit is mounted in the right-hand part of the frame.

Use of protective devices with an intermittent operation regime is one of the methods employed in the automatic cathodic protection of underground structures. They are designed to maintain for a long time the protective potential on underground and marine structures with respect to the environment. These devices can be turned off for long periods thus providing energy economy and increased service life of grounding anodes.

The Academy of Municipal Economy designed the cathode station IDS-AKKh which can supply current for up to 20 minutes and provides automatic switching of the polarization current when the value of the potential on structure decreases to a fixed level. This unit is provided with a transistorized time relay which is switched by a measuring circuit which has an input resistance of 100-150 kohm. The power of the unit is 2.5, supply voltage 220 VAC, rectified voltage 50 V, rectified current 50 A, protective potential can be controlled within 0.3-2.5 V. The unit weighs 100 kg.

The functional schematic diagram of the cathode station IKS-AKKh is shown in Figure 7.

The unit is connected to single-phase 220 VAC, 50 hertz line. Voltage is supplied through safety fuses $ПР_2$ and $ПР_3$ to rotary switch ПВ. Safety fuse $ПР_1$ and switch BK are located in a supply line of the control circuit.

The power rectifying device consists of a full-wave circuit with a center tap on thyristors D_1 and D_2 which perform the rectifying and controlling functions. The rectifier is connected to the secondary winding of the power transformer TP_2. The cathode protection circuit (for example,

reinforced waterpipe and grounding anode) provide the load for the rectifier. Current measuring ammeter A and safety fuse ΠP_4 are located at the rectifier output. The voltage value at the output is controlled by the RC bridge making it possible to change the conduction angle of thyristors D_1 and D_2 within a wide range. The phase-shifting device consists of auxiliary step-down transformer TP_1, fixed capacity C_1, and variable resistor R_1 which determines the required conduction angle of thyristors D_1 and D_2. Resistor R_2 and diodes D_3 and D_4 are connected to the control electrodes of the thyristors to limit the current in the control circuit and to prevent the appearance of a reverse voltage on D_1 and D_2.

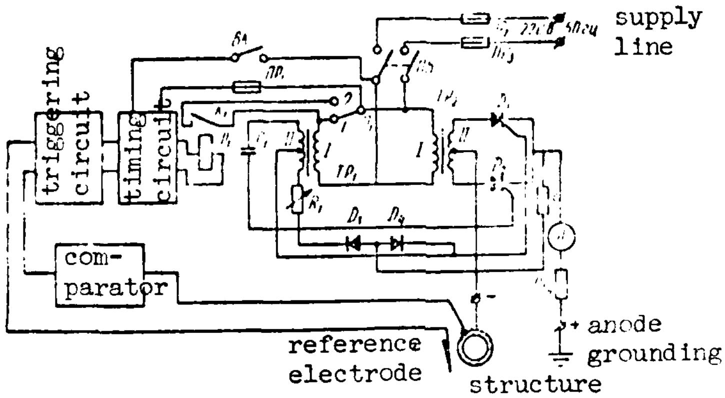


Figure 7. Functional schematic diagram of pulsed cathode station type IKS-AKKh

Under manual control, switch Π_1 (in position (1)) connects the primary winding of the transformer TP_1 to the 220 VAC line. Variable resistor R_1 controls voltage and current in the cathodic protection circuit. In this condition the IKS-AKKh unit operates as a conventional cathode station with a manually set control of the output voltage in the 10-60 V range.

When the switch Π_1 is put into the second position, relay P_1 is put in series with winding I of TP_1. Relay P_1 serves as the collector load of the output stage of the electronic time relay which determines the pulse duration of cathode current produced by the station. During operation of the relay P_1, the feed circuit of the phase-shifting device closes and current

appears at the output of the thyristor rectifiers D_1 and D_2. The duration of current flow is limited by the timing circuit and can be set from 30 seconds to 20 minutes.

The trigger circuit, which is connected in series with the stabilized reference voltage and reference electrode, serves as a controlling device for the IKS-AKKh. The input resistance of the signal circuit could reach 150-100 kohm, while current in the same circuit does not exceed 1 μA. By controlling the reference voltage, it is possible to operate the trigger circuit over a wide range of signal voltage (from 50 mV to 4-5 V).

The automatic IKS-AKKh device turns on when the protective potential at the input of the electronic device (which records the potential on the structure with respect to the surrounding soil) drops below the established limiting value. At this time the unit produces a cathodic current pulse which lasts from 30 seconds to 20 minutes (depending on the time delay) and switches off again. It remains in this state until the protective potential on the underground structure exceeds the established limit. Thus, the duty cycle of the IKS-AKKh unit could be low with a consequent saving of electric energy.

The IKS-AKKh unit is mounted in standardized steel cabinet. Illumination bulb (1) is attached at the top of the frame (Figure 8). There is an opening underneath containing the electronic unit (transistorized time delay and trigger circuit with power supply). This opening is provided with a two-hinged door. At the right side of this opening are located the DC ammeter (3) and voltmeter (5). Thyristors ВКДУ-150 (4) are located behind the front panel, with their coolers in the ventilation duct. The power transformer TP_1 (7) is installed in the lower part of the frame. A panel containing safety fuses ΠP_1 and ΠP_2 (6); rotary switch (8), plug receptacle (10) and safety fuse ΠP_5 (9) is located at the right-hand side of the transformer.

Electric circuits of the described anticorrosion devices are given in Chapter IV, which covers the adjustment and operation of these devices.

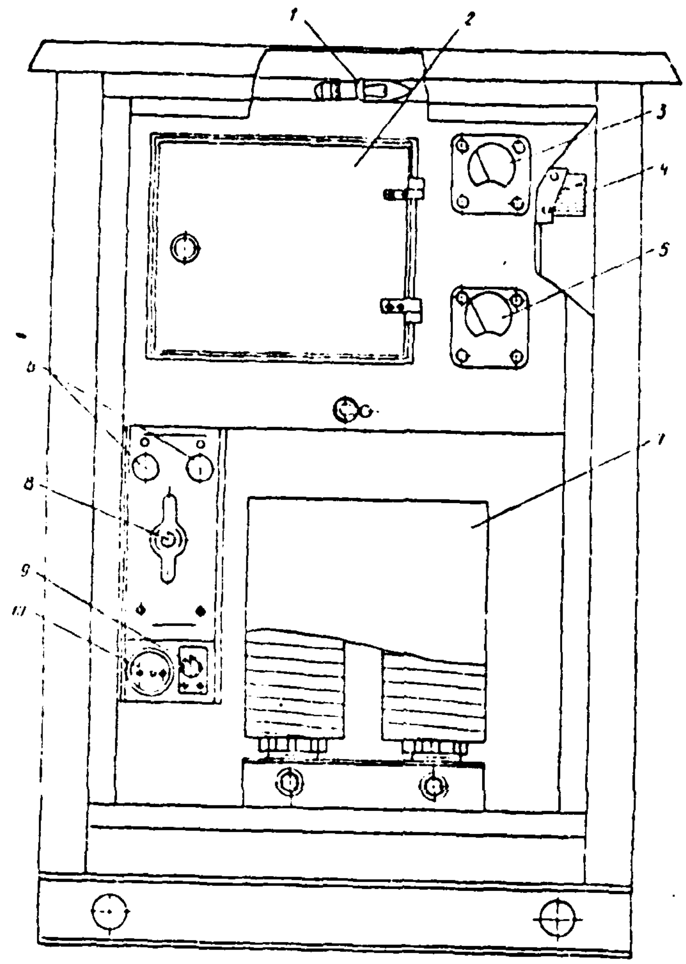


Figure 8. Automatic cathode station type IKS-AKKh

(location of subassemblies)

CHAPTER 2

COMPONENTS OF AUTOMATIC PROTECTIVE DEVICES AND THEIR RELATION TO RELIABILITY

1. RECTIFIERS DESIGNED FOR USE IN ANTICORROSION DEVICES

Protective devices for underground structures, against corrosion produced by stray currents, provide cathodic polarization of metal, i.e., produce protective potentials. In the case of powered electrodraining and cathodic protection, the negative lead of the DC source is attached to the underground structure. A transformer equipped with a rectifier which transforms the AC into DC can be such a source.

A rectifier can be represented as shown in block diagram, Figure 9.

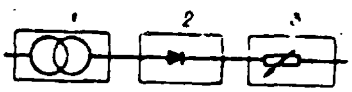


Figure 9. Rectifier block diagram

The rectifier circuit (2) transforms the AC into DC which passes through the load (3).

Circuits of semiconductor rectifiers can be classified according to output power: devices of low power (a few kilowatts), medium power (several tens of kilowatts), and high power devices. These devices can be supplied with power from single-phase or three-phase sources, and they could be either regulated or unregulated. Single- and three-phase rectifiers can in turn be classified into circuits with a center tap, bridge-type and others, depending on the rectifier switching circuit and connections to the transformer windings. Sometimes rectifiers are classified according to several other characteristics, such as the nature of the load (passive or reactive), the voltage (low, medium, high), and the frequency of the rectified current, etc.

This chapter considers only rectifier circuits of low and medium power which are used in anticorrosion protection devices.

a. Single-Phase, Full-Wave, Center Tapped Circuit. Figure 10 shows this type of circuit. This circuit is sometimes called two-phase because the secondary winding of the power transformer produces two voltages shifted by 180° from each other. This circuit operates in the following manner. During the first half-period when the potential of, for example, the upper half-winding of the transformer is positive with respect to the midpoint 0, the anode of rectifier B_1 is more positive than its cathode and the rectifier B_1 is conducting. As a result a positive phase voltage of the secondary transformer U_2 winding will be applied to the load R_L during the first half-period. The rectifier B_2 will not conduct during the first half-period because a reverse voltage twice as large as the voltage of the secondary winding will be applied to it. During the next half-period the voltage polarity on the transformer windings will be reversed and the rectifiers will exchange their roles. A transfer of current from B_1 to B_2 takes place when the voltage in the transformer secondary winding changes its sign. A transfer of current from one rectifier to another is called commutation. During the second half-period the load R_L receives the voltage U_2, the sign of which will be the same as during the first half-period. The single-phase full-wave circuit possesses the following characteristics:

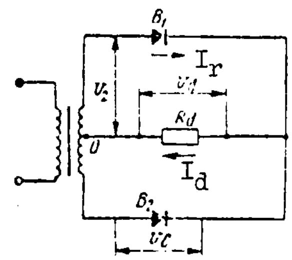


Figure 10. Circuit of a single-phase, full-wave rectifier

(1) The average rectified voltage $U_d = 0.9\ U_{2ph}$ where U_{2ph} is the rms value of the voltage of the secondary transformer winding.

(2) Maximum value of the reverse voltage U_{rev} is equal to double the secondary voltage, or it exceeds by 2.84 times the rms phase voltage, $U_{rev} = 2.84\ U_{2ph}$.

(3) Average value of rectified current is

$$I_d = \frac{U_d}{R_d} .$$

(4) Average value of rectified current passing through a rectifier is

$$I_{r\ av} = \frac{I_d}{2}.$$

(5) Maximum amplitude current value passing through the rectifier is

$$I_{r\ max} = I_{2\ max} = \frac{\pi}{2} I_d.$$

(6) RMS value of the current passing through the rectifier is

$$I_r = \frac{\pi}{4} I_d.$$

(7) RMS value of the current in the transformer secondary winding is

$$I_2 = \frac{\pi}{2\sqrt{2}} I_d.$$

(8) RMS value of the current in the primary transformed winding is

$$I_1 = \frac{\pi}{2\sqrt{2}} \cdot \frac{I_d}{K_t}.$$

where K_t is the transformer transformation coefficient.

In order to evaluate the performarce of rectifiers in rectifying circuits, the utilization factor of rectifiers with respect to voltage is used:

$$K_v = \frac{U_{rev}}{U_d}$$

and with respect to current

$$K_i = \frac{I_r}{I_d}.$$

For the circuit under consideration

$$K_v = \pi \quad \text{and} \quad K_i = \frac{\pi}{4}.$$

b. Single-Phase Bridge Circuit. A single-phase bridge rectifier (Figure 11) operates in the following way. Assume that at the beginning the secondary transformer winding A is positive with respect to its other end during the first half-period. In this case rectifiers B_1 and B_3 conduct and

the voltage of the secondary transformer winding U_2 is applied to load R_d. Rectifiers B_2 and B_4 are not conducting during this interval because the secondary winding voltage is reversed in sign. When the voltage polarity in the transformer winding changes sign, rectifiers B_2 and B_4 conduct and B_1 and B_3 do not. Thus, the circuit rectifiers operate in pairs by passing both half-waves of the AC voltage through the load resistor.

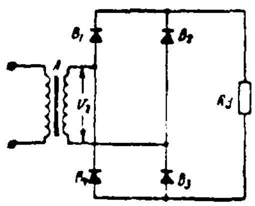


Figure 11. Circuit of a single-phase bridge rectifier

The rectified voltage appears in the form of uni-polar waves of the supplied AC voltage with the ripple frequency equaling twice the input frequency.

(1) Average value of the rectified voltage is

$$U_d = 0.9U_{2ph}.$$

(2) Maximum value of a reverse voltage in the rectifier is

$$U_{rev} = 1.42U_{2ph}$$

(3) Average value of current passing through the rectifier

$$I_{r\ ph} = \frac{I_d}{2}.$$

(4) RMS current value passing through the rectifier

$$I_r = \frac{\pi}{4} I_d.$$

(5) RMS current value in the transformed secondary winding

$$I_2 = \frac{\pi}{2\sqrt{2}} I_d.$$

(6) Acting current value in the primary transformer winding

$$I_1 = \frac{\pi}{2\sqrt{2}K_t} I_d.$$

(7) Utilization factor of rectifiers is $K_U = 1.57$, $K_1 = 0.78$.

2. POWER SEMICONDUCTOR RECTIFIERS

It is known from practice with anticorrosion protection devices that average currents of powered draining devices could reach 300 A in many cases, and those of cathode stations 50 A.

A rectifier is assembled from power semiconductor rectifiers (diodes), which could be either germanium or silicon. Silicon diodes have found wider application lately.

The rectifier block is one of the main elements of the anticorrosion protection system. Reliable operation of this unit insures first of all a high efficiency of the entire system of anticorrosion protection. Reliable performance of the rectifying unit is determined by the quality of the diodes, the conditions of operation, and proper use.

Table 1 presents basic technological characteristics of power silicon diodes.

Diodes BK2-100 and BK2-200 are used primarily in circuits of electric drainage and cathode stations.

Nominal diode current, I_{nr}, is defined as an average DC current which produces the maximum allowable heating under steady state operation, at a nominal reverse voltage, air temperature of 40°C, and all other devices are cooled.

Nominal DC is considered to be the average current value measured by a magnetoelectric ammeter in a single-phase half-wave rectifying circuit operating under active load. This current does not cause excess heating and irreversable changes of the diode characteristics.

Normal reverse voltage $U_{n\ rev}$ is the value of the reverse voltage at which the diode can operate for a long time.

Nominal forward voltage drop in diode, ΔU_{nr}, is an average drop per period while passing a nominal voltage through the rectifier.

Depending on value of the nominal reverse voltage, diodes are classified into 14 groups (GOST 10662-63): 0.5; 1; 1.5; 2; 2.5; 3; 3.5; 4; 5; 6; 7; 8; 9; 10 V and according to the reverse voltage rating respectively: 50, 100, 150, 200, 250, 300, 350, 400, 500, 600, 700, 800, 900, 1000 V.

According to their nominal forward voltage drops, diodes are classified into six groups: A, B, C, D, E, F.

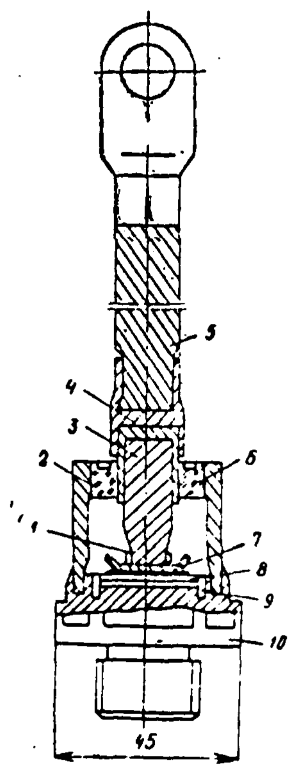
Table 1. Basic parameters of silicon diodes

Parameter	Type of Rectifier					
	BK2-10	BK2-50	BK2-100	BK2-200	BKB2-350	BKB2-500
Nominal power, kW	0.3-3.3	1.6-16.6	3.3-33.3	6.6-66.6	11.6-116.6	16.6-166.6
Nominal current, A	10	50	100	200	350	500
Minimum reverse voltage, V	100-1000					
Nominal forward voltage drop, V	0.4-0.7	0.4-0.7	0.4-0.7	0.4-0.7	0.4-0.75	0.5-0.9
Size, mm	72x42x106	75x44x272	70x80x330	70x80x330	62x323	--
Weight, kg						
Without cooler	0.044±5%	0.180±5%	--	0.51±5%	--	--
With cooler	0.130±5%	1.280±5%	--	2.2±5%	--	--

Diodes of group A have a forward voltage drop equaling 0.4-0.5; B, 0.51-0.6; C, 0.61-0.7; D, 0.71-0.8; E, 0.81-0.9 and F, 0.91-1 V. Diodes of the first three groups are the most widely used in anticorrosion devices because of their lower voltage drop.

The reverse current value is also standardized for power diodes. This value is considered to be an average per period which passes the rough diode in a reverse direction with a nominal reverse voltage applied at a junction temperature of 140°C. The reverse current value for diodes from 10-100 A should not exceed more than 0.02% the rated forward current; and for diodes above 100 A, it should be not higher than 0.01%.

Figure 12 shows silicon rectifier type BK2-200, and Figure 13 shows the heat sink for this rectifier.



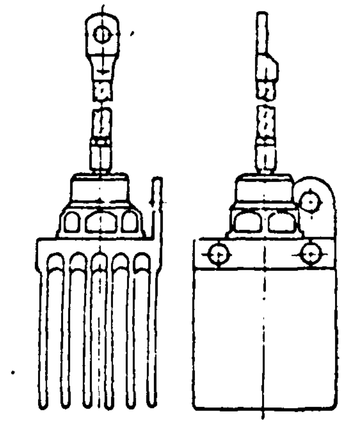


Figure 12. Design of silicon rectifier

Figure 13. Typical rectifier heat sink

The single crystal silicon disk (8) in Figure 12 is 25mm in diameter with metal contacts to the p-n junction. This disk is soldered between thermocompensating (7) and (9) tungsten plates. The upper (7) plate is 22mm in diameter and 1.2mm thick, the lower (9) is 25mm in diameter and 1.2mm thick.

These three plates constitute the rectifying element. A copper cup is soldered to the upper plate (7). Plate (7) and (9) are intended for lowering the mechanical stresses in silicon which originate due to the thermal deformations of silicon and also of the copper contacts. The linear temperature coefficient expansion of silicon and tungsten are almost identical in value.

The rectifying element is placed in a hermetically sealed metal box consisting of a copper base (10) and metal-glass cover. This is needed for protection of the rectifying element from moisture, dirt, mechanical damage, and for good heat dissipation properties. Steel ring (4) is isolated from glass bushing (6), which is equipped with flexible voltage lead (3), by glass insulation (2).

The rectifier is assembled in the following manner: the rectifying element is soldered to the box base (10); a Teflon gasket is placed under the box cover; the internal flexible lead is passed into cup (1) which is filled with molten solder; a hermetic seal is accomplished by compression; an intermediate ring with a flexible external lead (5) with adapter is soldered to bushing (6). The external flexible lead with adapter (anode) and base with a pin (cathode) serve as the rectifier electrodes. The pin on the base is needed for the heat radiator attachment.

The hexahedral radiator is the standard heat sink (Figure 13). The radiator has receptacles for attachment of the conducting lines. The rectifier designation is noted on the cooling fins with an indication of the current direction. For example, diode BK2-200-7/B means: B for the diode, K for silicon; 2 for diffusion type; 200 for a nominal current of 200 A; 7 designates seventh class, Б for group Б (with a forward voltage drop of 0.51-0 6 V). The direction of current is indicated by an arrow.

Characteristics of diodes should be taken into consideration when designing electric draining devices and cathode stations. Static and dynamic voltage-current characteristics are the bases for rectifier selection. The first represents the current dependence on the rectifier voltage; DC characteristic in forward and reverse directions are taken separately on DC. Dynamic volt-ampere characteristic represents dependence of instantaneous current values on instantaneous voltage values. It is recorded simultaneously in forward and reverse directions when a sinusoidal voltage of the operating frequency is applied to the rectifier. The semidynamic volt-ampere

characteristic is shown by a graphic representation of the dependence of average rectifier current value on the average value of the applied forward voltage. This characteristic if recorded separately in the forward and reverse directions when the diode is connected to a source of single-phase sinusoidal voltage of 50 Hz.

Figure 14 shows an ideal volt-ampere characteristic of a silicon diode. For convenience during calculations the forward branch of the static volt-ampere characteristic is represented by two straight sections. The diode voltage ΔU_r when current I_r passes through it is

$$\Delta U_r = U_{tr} + I_r R_r \qquad (2\text{-}1)$$

where U_{tr} is the threshold diode voltage, V; R_r is the diode resistance, ohm.

The diode resistance value can be determined from the volt-ampere characteristic. It is numerically equal to cotangent of the slope angle of the second rectilinear part of the characteristic

$$R_r = \mathrm{cotg}\,\gamma \qquad (2\text{-}2)$$

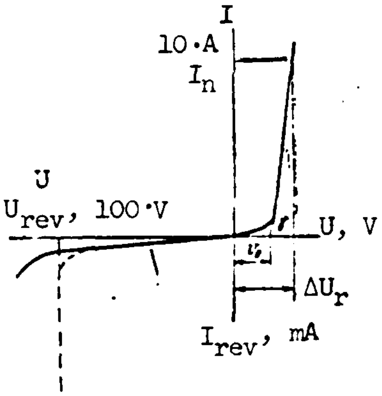


Figure 14. Volt-ampere characteristic

The forward branch of the classified characteristic is

$$\Delta U_{dr} = 0.5U_{tr} + I_{dr} R_r \qquad (2\text{-}3)$$

where ΔU_{dr} and I_{dr} represent the average diode voltage and current drop per period, respectively.

The value of the threshold voltage U_{tr} depends on semiconductor material properties from which the diode is made; the diode resistance value depends on the area of p-n junction, and the ohmic resistance of the base and contacts. Table 2 presents values of ΔU_{dr}, U_{tr} and R_r for diodes type BK2-200.

Table 2. Characteristics of BK2-200 diodes

U_{dr}, V	0.45	0.55	0.65
U_{tr}, V	0.79	0.91	1.02
R_r, 10^{-3} ohm	0.28	0.48	0.69

The threshold voltage in semiconductor diodes results in a relatively low sensitivity of polarized electric draining units which require the use of power diodes.

A periodic checking of the characteristics of rectifiers is necessary to detect their aging and replacement time. The characteristics of new diodes should resemble as close as possible the diodes to be replaced. Diode characteristics are also needed for calculation of the thermal properties of the rectifier block.

The characteristics of power diodes used in anticorrosion devices should be recorded on special test benches, in order to obtain a qualitative determination of their parameters. The threshold voltage, resistance, reverse current, and the class with respect to an average forward voltage drop should be determined for each diode. The bench circuit for testing the forward branch of the static volt-ampere characteristic should consist of a three-phase controllable autotransformer of 1 KVA, a three-phase transformer of the same power with a voltage ratio of 220/2.5, and of a rectifier assembled on the basis of the three-phase bridge circuit with six silicon low-voltage diodes in standard cooling radiators. The rectifier assembly should deliver up to 200 A. Leads are connected to the diode under study. The diode voltage drop should be measured at two values of current. For example, at 50 and 200 A for type BK2-200, i.e., at 25% of the nominal current and at the nominal current. The approximate volt-ampere static characteristic is plotted on the basis of two points and the intersection of this plotted line with the voltage axis determines the value of U_{tr} (Figure 11).

It should be kept in mind that the voltage drop changes in time after the current is turned on and the characteristic drifts. Therefore, all rectifiers should be tested during the same time interval after the current

is turned on, for example, in 5 seconds. The internal resistance of rectifiers can be determined from the formula

$$R_r = \frac{\Delta U_r - U_{tr}}{I_r} \text{ ohm} \qquad (2\text{-}4)$$

If the internal diode resistance increases in time, this indicates that the silicon discs have become separated or the compression strand contact has deteriorated. In any case, an increase in R_r signifies an intensive aging of diodes.

Reverse branches of the static volt-ampere characteristic of diodes should be tested according to schematic diagram shown in Figure 15a. The alternating voltage of 50 Hz in this Figure is controlled by a laboratory autotransformer (1) and is passed to the step-up transformer (2) having the transformation ratio of 1:10.

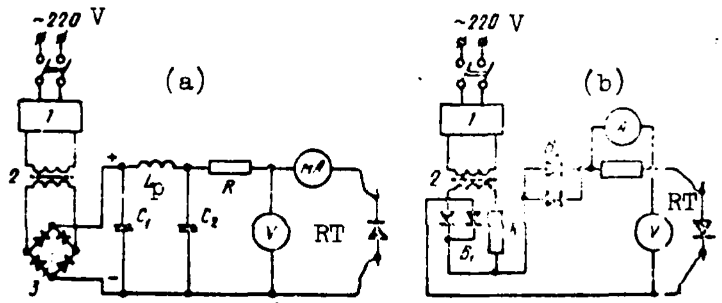


Figure 15. Testing circuits for silicon diodes
(a) recording the reverse branch of the static characteristic;
(b) recording the forward branch of volt-ampere characteristic.

The rectified voltage from rectifier (3) is filtered through a Π-section filter (C_1, C_2 and L) and flows to the rectifier under test (RT) through K-2 current limiter resistance, R.

In order to improve the testing accuracy, it is necessary to have a shunt switch across the milliameter. The value of reverse current should not exceed 20 mA when diodes of type BK2-200 are tested. An increase in the reverse current signifies that the insulation of the p-n junction structure is damaged.

Figure 15b shows the test circuit for a forward branch of the volt-ampere characteristic. This circuit consists of a controllable autotransformer

(1); transformer (2) with a power of 15 kVA and a voltage ratio of 220/15; supplementary resistance R = 0.05 ohm, 300 A; two groups of supplementary diodes B_1 and B_2. The resistance R is the active load of the circuit and insures the flow of the sinusoidal current through RT. The diode B2 provides half-wave current rectification in the RT circuit, and diodes B_1 maintain the transformer load during the negative voltage half-period. Recording the classified characteristics is necessary for testing diodes for an average voltage drop, i.e., to determine the diode group. The ammeter and voltmeter in the test scheme are instruments of the magnetoelectric system.

The hermetic seal of all rectifiers should be tested. For this purpose a cold diode is submerged into hot caster oil or glycerin (125°C). The appearance of air bubbles indicate a poor seal which would damage insulation and distort the reverse characteristics. Diodes with poor hermetic seals should not be used.

A parallel connection of semiconductor diodes is used in circuits of many automatic protective devices. This type of connection is used in those cases when the nominal output current of the unit, I_{nu}, exceeds the nominal current rating of a single diode. Differences in the forward volt-ampere characteristics of diodes connected in parallel causes nonuniformity in the current distribution between them. This can also be corrected by different sistances in the mounting connections (leads, bus wires).

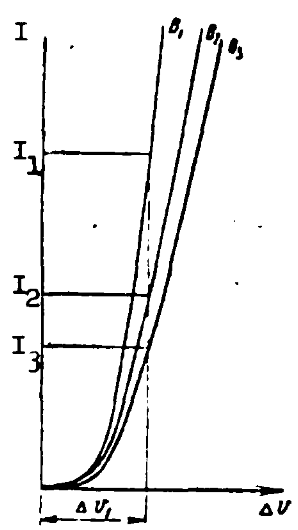


Figure 16. Current distribution in diodes connected in parallel.

Figure 16 shows volt-ampere characteristics of three diodes with different values of R_r. When these diodes are connected in parallel, the applied voltage ΔU_1 is the same for all. However, it is evident from Figure 16 that currents passing through diodes (I_1, I_2 and I_3) will significantly differ from each other. Therefore, during design of the parallel connection circuit of diodes it is necessary to select very carefully their characteristics, or to use supplementary means for securing a uniform current distribution. According to GOST 10662-63, diodes used in parallel should not differ in their ΔU_{dr} characteristic by more than 0.02 V.

Use of inductive current distributors (L-4) in powered transforming devices provides a uniform current distribution in parallel branches. However, devices of this type can not be used in anticorrosion units because of their size. In many cases equalizing resistances are used in series with each diode, the value of which significantly exceeds (by 2-3 orders) the internal resistance of the diodes. When value of the equalizing resistance is uniform, a uniform current distribution is insured through diodes connected in parallel. However, this type of circuit increases the energy losses and decreases efficiency in some cases.

The number of diodes needed for a parallel connection in one phase of a center tapped circuit or in one part of the bridge circuit can be calculated from the formula

$$N_{par} = \frac{I_{nu}}{mI_{nr} K_{cd}} K_{c\ res} \qquad (2\text{-}5)$$

where m is the number of phases in the rectifying circuit, usually m = 2 for these systems; K_{cd} is the coefficient accounting for nonuniform current distribution between parallel circuits, $K_{cd} = 0.8 - 0.9$; $K_{c\ res}$ is the current reserve which is equal to 1.1-1.3 for preliminary calculation.

The selected number of diodes connected in parallel should be verified with respect to heat dissipation. The method for this verification is described in section 3 of this chapter.

As a rule, the voltage output of the anticorrosion system is small. Therefore, values of the applied reverse voltages per diode are also small. However, it should be kept in mind that electric craining devices in anticorrosion systems are connected electrically with the network of the rail system. The presence of atmospheric and commutation overvoltages is possible for electrified rail systems. Converting units at substations of these systems should be properly protected from overvoltages. This can be accomplished by lightning arresters and circuits consisting of resistors and capacitors.

Overvoltages originating in the rail system could increase the reverse voltage in the rectifiers of anticorrosion units. There were many cases when rectifiers in electric draining units were damaged by large

discharges. There is no special protection for anticorrosion units against overvoltages. If rectifiers are damaged frequently due to excessive discharges, diodes of type ВКДЛ (controlled avalanche-type) can be used in place of conventional power diodes.

Diodes of type ВКДЛ differ from conventional diodes by their ability to work for a short time under overvoltage conditions. Their p-n junction has a special design which provides a considerably wider range of volumetric charge at the p-n junction surface (so-called protecting ring). This excludes a local avalanche breakdown in a diode on the periphery of the silicon disc. Homogeneous original silicon, which provides a uniform distribution of the avalanche breakdown on the entire area of the p-n junction, is used in the central part of the p-n junction. A total value of allowable voltage rating during passing of a reverse current in such junctions exceeds usually by several orders that of conventional p-n junctions with surface leakage. The avalanche breakdown in diodes with controlled avalanche, which originates when excess reverse voltage is applied, is not transformed into heat and is reversible.

The reverse branch of the volt-ampere characteristic of a diode with controlled avalanche has a sharp inflection at the limiting voltage level of V_{av}. This limiting voltage is called the avalanche voltage (broken line in Figure 14). If a reverse voltage is applied which exceeds the avalanche voltage, a reversible avalanche breakdown takes place limiting the voltage on diode, and a high reverse current flows.

Table 3. Basic parameters of silicon rectifiers with controlled avalanche

Parameter	Type of Rectifier		
	ВКДЛ-100	ВКДЛ-200	ВКДЛ-350
Nominal power, kW	10-23.3	20-46.6	35-81.6
Nominal current, A	100	200	350
Maximum allowable value of reverse voltage, V	300-700	300-700	300-700
Nominal forward voltage drop, V	0.4-0.65	0.4-0.65	0.4-0.7
Size, mm	70x80x330	70x80x330	62x323
Weight, kg			
without cooler	0.51±5%	0.51±5%	0.51±5%
with cooler	2.2±5%	2.2±5%	1.2±5%

3. THYRISTORS

A special type of semiconductor device called thyristors have been used lately in automatic protective systems. While two-terminal semiconductor diodes serve only as rectifiers of AC into DC, thyristors are used for designing a great variety of different rectifiers of the electric energy.

Thyristors used in anticorrosion systems (automatic electric drainages and cathode stations) are designed, as a rule, on the basis of a four-layer single crystal n-p-n-p structure (Figure 17). The two middle layers are p- and n-bases, and the side layers are p- and n-emitters. The emitter electrodes are connected into the power network. The negative emitter electrode serves as the cathode and the positive as the anode. The base p-electrode is the controlling electrode. The p-n junction between the negative emitter and p-base is called the cathode junction and that between the positive emitter and n-base is the anode junction. The p-n junction between p- and n-bases are called the collector junction. Thyristors differ from transistors by the presence of the fourth region in the single crystal structure.

When thyristors are externally switched off, blocking layers appear at each p-n junction which produce corresponding potential barriers. After the gate and anode are switched on in the presence of a relatively low anode voltage (polarity of the controlling chain is shown in Figure 17) the voltage U_c decreases the potential barrier of the cathode junction and this triggers the injection of electrons from n-emitter into p-base. Part of these electrons recombine with holes of the p-base and the remaining part reaches the n-base through the collector electrode. The collector electrodes form a volume charge of nonequilibrium majority carriers (electrons) in the n-base. This charge controls the second emitter by lowering the potential barrier of the third p-n junction. At the same time holes from the p-emitter (anode) are injected into the n-base. Part of these holes recombine with electrons and the remainder enter the p-base and form a volume charge of nonequilibrium majority carriers (holes). The charge triggers the second injection of electrons from the n-emitter into the p-base. In this manner an avalanche is produced leading to the increase of anode current flowing through the thyristor. If the gate is switched off after the thyristor is turned on, the flow of anode current through a thyristor will not change because all bases are

filled with nonequilibrium majority carriers which provide the next injection from the emitters.

This property of thyristors makes them completely different from transistors. The value of current in the collector of a transistor depends upon a constant current in the controlling circuit (base); but when the controlling circuit is switched off, the collector current of the transistor is also switched off. As opposed to the transistor, the thyristor switches on when a current pulse is applied to the gate. Even a complete switching off of the gate circuit does not influence the current in the power circuit when the thyristor is operating. Thyristors can be switched off only when the anode voltage ($U_a = 0$) is removed.

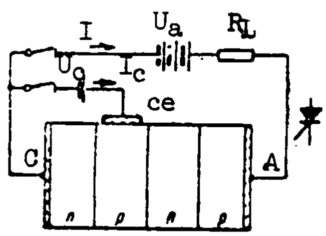


Figure 17. Thyristor design.

In addition to the gate control circuit, the thyristor can be switched on by increasing the anode voltage when the controlling circuit is switched off. The anode voltage which switches on the thyristor is called the switching voltage. Figure 18 shows the volt-ampere characteristic of a four-layer thyristor.

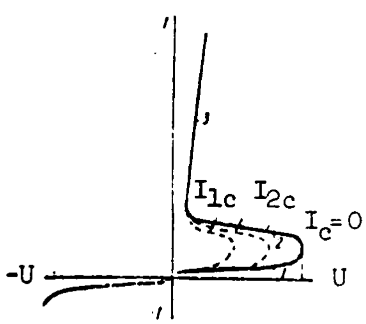


Figure 18. Volt-ampere characteristic of a thyristor.

Section (1) of the straight branch of this characteristic corresponds to the non-conducting closed state of the thyristor. After the voltage reaches the value of U_{sw} the thyristor switches on and section (2) indicates that thyristors attain an avalanche switching state. Section (3) of the volt-ampere characteristic corresponds to a switched state of the thyristor and represents the region of operation.

The switching process of the thyristor, i.e., going from the state of low conductance to high conductance, when the gate circuit is closed, does not differ in principle from thyristor switching after the gate circuit is triggered by a voltage pulse [5]. Flow of the gate current through thyristors decreases only the anode voltage at which thyristor is switched. The course of the volt-ampere characteristics of a thyristor with switched-on gate circuit is shown by broken lines in Figure 18 for gate current I_{1c} and I_{2c} when $I_{1c} > I_{2c}$.

The reverse volt-ampere characteristic of thyristors resembles that of the diode. The electrical stability of thyristor to which a reverse voltage is applied is determined mainly by the characteristic of the third p-n junction. The reason is that the p-base is highly doped, and this determines the minimum breakdown voltage of this junction.

Table 4. Basic parameters of power thyristors

Parameter	Type of Thyristor			
	ВКДЛ-50	ВКДЛ-100	ВКДЛ-150	ВКДЛ-200
Nominal power, kW	0.8-11.6	1.6-23.3	2.5-35	3.3-46.6
Nominal current, A	50	100	150	200
Nominal reverse voltage, V	50-1000	50-1000	50-1000	50-1000
Nominal forward voltage drop which does not exceed	1.25	0.9	0.75	0.9
Size, mm	70x80x327	70x80x327	70x80x327	62x321
Weight, kg				
without heat sink	0.45±0.03	0.45±0.03	0.45±0.03	0.45±0.03
with heat sink	2.14±0.1	2.14±0.1	2.14±0.1	1.12±0.05

Nominal currents, nominal reverse voltages and nominal forward voltage drops, which are determined from the volt-ampere characteristics, have the same physical sense for thyristors as for conventional diodes.

With respect to voltage classes, thyristors resemble power diodes, and with respect to groups of forward voltage drops, they differ from diodes. Thyristors of group A have a forward voltage drop up to 0.57 V; group B, 0.57-0.72 V; group C, 0.72-0.87 V; group D, 0.87-1.01 V; and group E, 1.01-1.4 V. The thyristor resistance is determined by the cotangent value of the slope of the operating section of the forward branch of volt-ampere characteristic.

The rate with which the anode current increases is one additional property of thyristors, which characterizes the thyristor as a power semiconductor rectifier. This property also characterizes the power circuit into which the thyristor is connected. In order to secure a reliable and long service life, it is necessary to limit the rate of increase of anode current. This is explained by the fact that the gate current during the initial time after switching on the gate circuit is switched on is nonuniformly distributed in the thyristor structure and localized in the area adjacent to the control electrode. Therefore, the avalanche *switching process* develops in this area first and it requires up to 200 μsec for this process to spread over the entire structure for the type ВКДУ-150 thyristor. When the inductance of the power circuit is low, the current can reach the maximum value in a few microseconds. In this case a high current density originates within the thyristor structure directly adjacent to control electrode, and this in turn produces rapid heating and damage to the thyristor. To avoid it, DC saturable reactors and reactance coils are connected in series with thyristors in the power circuit. The saturation time of an reactance coil can be determined approximately from

$$t_{sat} = \frac{WS\ \Delta B \cdot 10^{-4}}{U}\ \text{sec} \qquad (2\text{-}6)$$

where W is the number of windings in the reactance coil;

S is the cross-section area of a core, cm^2;

ΔB is the core induction changes, ml;

U is the maximum applied voltage, V.

The allowable rate of current increase recommended is usually up to 20 A/μsec.

Since the thyristors in circuits of automatic protective anti-corrosion devices are switched on from a controlling circuit, the characteristics of these circuits influence extensively the efficiency, performance, and stability of these devices. The maximum and minimum allowable current and voltage values which provide reliable switching of the thyristor, as well as the on and off switching times, are the most important characteristics of the controlling circuits. The same values, as a result, also determine the current pulse time in the gate circuit which is necessary to trigger the thyristor.

Dependence of the thyristor gate current I_c on controlling voltage is usually presented as shown in Figure 19. Here $r_{c\ min}$ and $r_{c\ max}$ represent

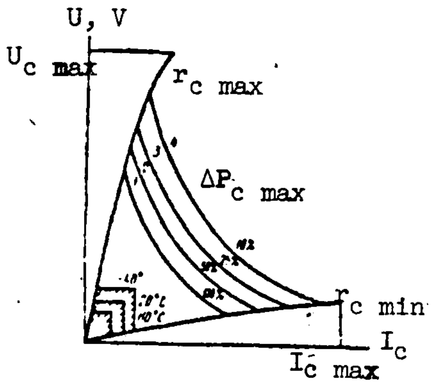


Figure 19. Control diagram of thyristor.

the limiting volt-ampere characteristics of the control circuit of this type of thyristor. Limiting characteristics are determined for thyristors having the highest resistance of control circuit at the highest operating temperature for a single crystal structure (110°C), and also for thyristors having the lowest resistance of control circuit at the lowest operating temperature (-40°C).

It should be noted that thyristors of the same type have, as a rule, a wide variation of the resistance values of the control electrode. Thus, for thyristors of type ВКДУ-150, this resistance can be 5 to 30 ohms.

In order not to exceed the maximum allowable temperature of the thyristor structure, power curves of the control circuit (1, 2, 3, 4 in Figure 19) are plotted for each type of thyristor for different durations of the control signal. The silicon structure will not be damaged if the

parameters of the control signal are located below and at the left-hand side of curves 1, 2, 3, 4 at a given relative signal duration. At the same time, current and voltage values should exceed some minimum values. These minimum values are shown at left lower part in Figure 19. The minimum control current and voltage values are dependent on temperature of the silicon single crystal structure. The current and voltage values of control circuit needed to switch on the thyristor decrease with increasing temperature.

Reliable switching on of thyristor will be insured if the actual control current and voltage values exceed the minimum values shown in Figure 19, i.e., the external characteristics of control circuits will pass above the boundary values but below curves 1, 2, 3, and 4.

The control current and voltage values which are used most frequently for thyristors at 25°C are given in Table 5.

Table 5. Current and voltage values of thyristor control circuit

Parameter	Thyristor With Respect to Nominal Current, A					
	10	25	50	100	150	200
I_c in A, not exceeding	0.2	0.2	0.3	0.3	0.3	0.3
U_c in V, not exceeding	7	7	7	8	8	8

Applications of thyristors at low temperatures requires an increase in the current of control circuit of up to 1.8-2 A. Since thyristors are controlled, as a rule, by pulses of given duration, the control current should be selected as a function of pulse duration. The control current value needed to switch the thyristor on remains practically unchanged when the duration of control pulse greater than 200 μsec. The duration of control pulse should exceed the normal switching time of thyristor, i.e., 8-20 μsec. Therefore, the minimum duration of the control pulse should be 20-25 μsec.

The switching off time of thyristors depends on the time needed for the restoration of its blocking properties in forward direction. The switching off time of a thyristor determines, in fact, the maximum frequency of operation. The switching off time of thyristors of type ВКДУ-150 is 80 to 200 μsec.

Consider a simple full-wave rectifier circuit with a center tapped secondary transformer winding. Both arms of the rectifier circuit contain thyristors T_1 and T_2 (Figure 20a), with load R_L also present in the circuit.

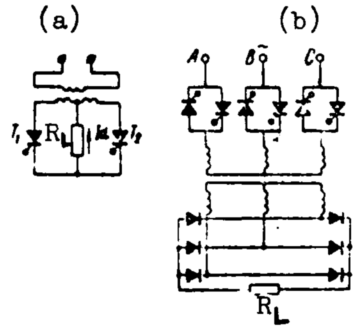


Figure 20. Controlling the voltage with thyristors:

(a) thyristors are connected in the secondary transformer winding;

(b) thyristors are connected in the primary transformer winding.

When thyristors are switched on, the control pulses should change the supply current phase of the gates of T_1 and T_2, depending on some signal. If the control pulse phase does not lag behind the phase of the transformer secondary voltage, the average value of the rectified voltage has a limiting value of U_{dn}. If the phase of the control pulse lags behind the phase of the transformer secondary voltage by some angle α, the average value of rectified voltage in this case will be less than U_{dn}. Thus, by changing the phase of the controlling pulse of the control circuit of thyristors, it is possible to control the average value of the rectified voltage. In the case under consideration the voltage was controlled by thyristors connected in the secondary of the transformer.

If a bridge rectifier circuit is used at the transformer output in the circuit of an automatic cathode station, thyristors can be included in the cathode bridge group, and conventional diodes in the anode group (so-called nonsymmetrical bridge circuit). Use of such a circuit would decrease the number of thyristors, as well as the number of controlling channels (two instead of four). The nonsymmetrical bridge circuit is unacceptable for high-power controlled rectifiers because of many shortcomings. But it can be used

in automatic anticorrosion devices the power of which, as a rule, does not exceed 3-5 kVA.

In addition to rectifiers with controlled voltage thyristors, other devices are designed which include thyristors in the primary of the transformer. In this case conventional power rectifiers (Figure 20b) are connected in the transformer secondary. Since step-down transformers are used in automatic cathode stations and powered electric draining units, the use of circuits with thyristor control in the primary can provide some advantages such as elimination of forced air cooling. The checking procedure of semiconductor devices is presented below. It can be only mentioned here that elimination of diodes requires a higher number of semiconductor components for the same nominal current, their reliability in general will be higher. An increase in the number of thyristors produces serious complications because of the requirement for more control circuits and the design of circuits to guarantee an uniform distribution of current in parallel thyristors. At the same time, a higher number of diodes in the transformer secondary does not complicate the whole system.

With respect to controlling thyristors in the transformer primary, it can be said that their quality must be higher, as compared with those in the transformer secondary because of the higher working voltage. At the same time the current in the primary is many times smaller than the current in the secondary (5-20 V). If thyristors are connected in this chain for 20-150 A current, they could reliably perform without any forced cooling.

Circuits with thyristors in the transformer secondary are presently more fully developed as compared to voltage control with thyristors in the primary. Therefore, the first circuits are used more often in automatic anticorrosion devices.

In order to secure reliable functioning of the rectifying block (controlled by thyristors) it is necessary to insure the turn-on of the thyristors at a precisely set time which is determined by a received signal (difference in potentials between the protected structure and the reference electrode). The thyristor control circuit can be designed with a horizontal or vertical principle. In the case of horizontal, the control circuit shifts the sinusoidal current of the supply line and the necessary control pulses are produced from it. A shift of the voltage phase, as a rule, is accomplished

by a phase inverter. The circuit of a phase inverter is shown in Figure 21a where a fixed capacitor and the bridge rectifier are in the transformer secondary. This bridge rectifier can be considered as a variable active resistance with a value determined by the signal voltage U_{in}:

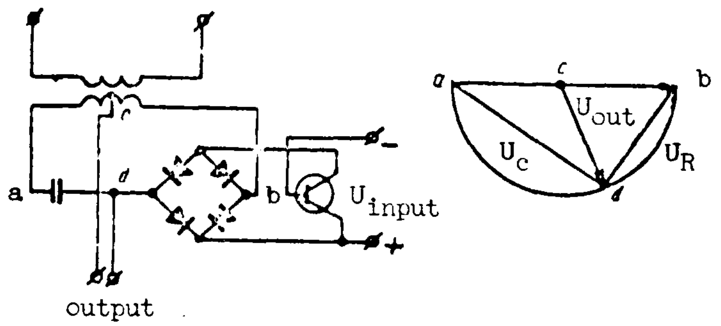


Figure 21. Phase inverter:

(a) circuit diagram;

(b) vector diagram.

It is evident from the vector diagram in Figure 21b that changes in the resistance value in the transformer secondary winding produces a shift of the voltage vector of the output phase inverter circuit ($U_{out} = U_{cd}$) which is taken from points c and d. The phase inverter circuit for the automatic cathode station designed by the Academy of Municipal Economy uses a fixed resistor and a variable inductive resistor (magnetic amplifier) in the transformer secondary. The phase of U_{out} shifts as a function of U_{in} when the magnetization current of the magnetic amplifier changes.

The principle of the vertical control provides for the formation of a saw-like voltage, comparing it with the control voltage, followed by the formation of rectangular pulses, the leading edge of which is determined by the comparison of the above voltages with respect to time. The vertical control circuits provide much higher qualitative control of the rectified output voltage. At the same time these circuits are more complex compared to horizontal control circuits.

Thyristors connected in series can be controlled either by separate channels or by one channel, provided the control circuits are connected in parallel. In order to equalize the input resistance of thyristors connected

in parallel, ohmic resistances of 20-25 ohms should be connected in series with the gate. When the current source of the control circuit is limited, the circuit is used with capacitors of 0.5 - 1 μf in the control circuit. In this case the circuit should have diodes protecting the thyristor gate against a reverse current.

Simple test stands, similar to those described earlier, should be used for testing the volt-ampere characteristics of thyristors. Special instrumentation is needed [4] for checking the on time switching of thyristors, allowable rate of increase of DC, and of off time switching of thyristors.

4. THERMAL TESTING OF SEMICONDUCTOR DEVICES

Temperature values of the p-n junction are classified as follows:

(a) Nominal temperature θ_n - the highest steady state operating temperature of the p-n junction. For domestic diodes θ_n = 140°C (GOST 10662-63). For thyristors θ_n = 110°C.

(b) Periodically allowable temperature θ' - the highest permissible temperature of the p-n junction when the diode is subjected to overload for a short time. For diodes θ' = 160°C. At this temperature they should be able to perform 5-10% above their capacity.

(c) One-time allowable temperature θ'' - the highest temperature of the single crystal structure which should not last longer than 20 msec due to rectifier overloading. This temperature is usually produced by a short-circuit. For diodes θ'' = 175°C. It should be noted that the temperature of the p-n junction influences the rectifier characteristics. For example, a diode voltage drop decreases with increasing temperature.

When electric current is passed through a rectifier, electric energy is dissipated in it, the value of which is determined by the current and the rectifier voltage drop. This energy heats

the rectifier and the heat sink. The heat flux produced in the silicon single crystal passes along the rectifier body and its lead. The heat flux from the rectifier body is passed to a heat sink and its environment. The p-n junction is the hottest, followed by the rectifier body and the heat sink. The temperature of the p-n junction increases until the amount of heat released in the diode becomes equal to that dissipated into the surrounding medium. The temperature of the p-n junction at a given value of the current flowing in the diode depends on the thermal properties of the diodes (sizes of rectifying and tungsten diodes, materials used for their manufacturing, their geometry, sizes and state of the contact surfaces) and the system of cooling.

In principle it is possible to use air, water and evaporative cooling of semiconductor devices. The air cooling can be either natural or forced. It is almost impossible to use water cooling of diodes and thyristors in anti-corrosion systems. Evaporative cooling is promising in power semiconductor technology. The selection of evaporating fluid is of importance in this case. This fluid should possess not only the equivalent heat of vaporization of water, but also an optimal saturation temperature. However, the systems of evaporative cooling have not yet received wide application.

Semiconductor devices in anticorrosion systems are cooled by air. In systems of type UD-AKKh (1969 production) and in some other units fans will be used with 10-12 msec supply of cooling air. The air stream flows around the heat sink of diodes and thyristors. Four-vaned fans will be used for 50 and 100 A rectifiers and six-vaned fans for 200 A rectifiers (Figure 10). The latter fan could cool an area of 720 cm^2.

Rectifiers and heat sinks can be joined either by screws or clamps. In order to improve the heat transfer, the use of lead-tin gaskets or coating the contact surfaces with silicon vaseline containing metal powder is suggested. In the case of a screwed joint, it is of importance to determine

the torque, to avoid excessive pressure at the place of contact. Until recently heat sinks made of copper were used. Presently they are made of aluminum because of lighter weight. However, the electrochemical difference in potentials of copper and aluminum became a problem. Therefore, the use of Silumin alloy is recommended, in addition to pure aluminum.

The temperature of p-n junctions of diodes and thyristors in anti-corrosion systems should be calculated for operational conditions characterized by high steady state loads. Under this condition the temperature $\theta_{(p-n)lg}$ can be expressed as follows

$$\theta_{(p-n)lg} = \theta_0 + \Delta\theta_{(p-n)lg} \tag{2-7}$$

where θ_0 is the environment temperature (cooling air). In calculation it is almost always assumed the less probable case when $\theta_0 = 40^oC$. $\Delta\theta_{(p-n)lg}$ is the temperature gradient between the p-n junction of diode or thyristor and environment.

The thermal resistance concept is used in thermal calculations for convenience. This resistance can be defined as an ability of a given body to resist the heat transfer. Therefore, the thermal resistance is designated by R_t and it is expressed in degree/W. By knowing the thermal resistance of diodes and thyristors it is possible to determine their temperature as a function of load and cooling rate. Thus, the temperature gradient is expressed by

$$\Delta\theta_{(p-n)lg} = R_t \Delta P_{r\ av} \tag{2-8}$$

where R_t is the rectifier thermal resistance; $\Delta P_{r\ av}$ is the average energy lost in rectifier during operation under load.

The method of electrothermal analogy is used in thermal calculations. The thermal resistance R_t of the system p-n junction - rectifier - environment can be presented as a sum of thermal resistances of individual elements of a heat transfer system.

The thermal resistance of a rectifier consists of external R_{t2} and internal R_{t1} thermal resistances. The internal thermal resistance considers the established temperature gradient between p-n junction and rectifier body. According to a study made at the Moscow Electrical Energy Institute this resistance is equal to 0.18 degree/W for BK2-200 diodes. The external thermal

resistance considers the temperature gradient between the rectifier body and environment and depends on the speed of cooling air, type of heat sink and cooling conditions.

Figure 22 shows the dependence of a total thermal resistance, R_t, of type BK2-200 rectifiers on the velocity of the cooling air. Curve 1 corresponds to conditions when the air stream passes through the heat sink fins and the rectifier body is under natural air circulation. The curve 2 corresponds to a simultaneous cooling of the rectifier and heat sink by an air stream [6, 7]. Use of these curves in calculations depends on the rectifier body design.

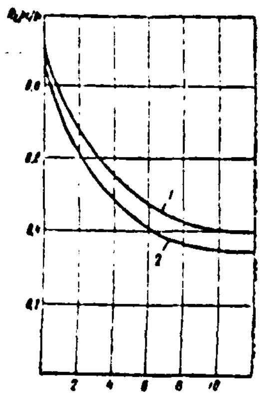


Figure 22. Thermal resistance of BK2-200 diodes as a function of the speed of cooling air.

Table 6 presents values of R_{t1} [4], R_{t2} and total values of R_t for several types of diodes and thyristors of type ВКДУ-150 at different velocities of the cooling air. It follows from this Table that about 50% of the thermal resistance belongs to the internal thermal resistance in the case of forced air cooling with the velocity of 10 msec. It amounts to 10-30% when the speed of air is zero.

The value of the external thermal resistance of diodes and thyristors does not depend practically on the speed of cooling air. It was proved by numerous measurements that R_{t1} = 0.196 degree/W in 90% of type ВКДУ -150 thyristors.

To determine the temperature of the p-n junction under the established regime $\theta_{(p-n)lg}$, we need to calculate average losses of $\Delta P_{r\ av}$ in

Table 6. Thermal resistance of semiconductor devices

Device	Type of cooling	Thermal resistance, degree/W		
		R_{t1}	R_{t2}	R_t
BK-50	Natural (air) V = 0	0.34	1.7	2.04
	Forced air V = 5 m/sec	0.34	0.6	0.94
	Forced air V = 10 m/sec	0.34	0.5	0.84
BK2-50	Natural (air) V = 0	0.32	1.62	1.94
	Forced air V = 5.2 m/sec	0.35	0.41	0.76
BK2-200	Natural (air) V = 0	0.14-0.2	1	1.14-1.2
	Forced air V = 5.2 m/sec	0.14-0.2	0.3	0.44-0.5
	Forced air V = 10 m/sec	0.14-0.2	0.2	0.34-0.4
ВКДУ -150	Natural (air) V = 0	0.12-0.26	1	1.12-1.26
	Forced air V = 5 m/sec	0.12-0.26	0.3	0.42-0.56
	Forced air V = 10 m/sec	0.12-0.26	0.18-0.21	0.30-0.47

expression (2-8). These losses in the rectifier will amount to product of Δ Ur av multiplied by an average rectifier current under conditions of prolonged operation. The value of $\Delta U_{r\ av}$ can be determined from expression (2-1) under conditions that average current $I_{r\ av}$ flows through rectifier

$$\Delta U_{r\ av} = V_{t\ r} + I_{r\ av} R_r \qquad (2\text{-}9)$$

and the average rectifier current is determined from (2-5)

$$I_{r\ av} = \frac{I_{1g\ est}}{mN_{par}\ K_{c\ d}} K_{c\ res}$$

Thus, the value of $\Delta P_{r\ av}$ is

$$\Delta P_{r\ av} = U_{t\ r}\ I_{r\ av} + AR_r I^2_{r\ av}\ W \qquad (2\text{-}10)$$

where A is the circuit coefficient. In the case of two-phase system A = 2.47, and for three-phase system A = 3.

The rectifiers of anticorrosion units perform under continuous or transient conditions. Short-circuit conditions produce the most stress. However, if the electric draining units and cathode stations are used according to instructions, the possibility of short circuits is minimal. Therefore, there is no point to check the p-n junctions for temperature limits under short circuit conditions.

The rectifying block of the TK-4 unit, which controls potentials of the tramway draining points, is connected directly to one of the traction substation lines. In this case short circuit current passes through this block when a short circuit takes place. Therefore, the power diodes in the output block of the TK-4 unit should be checked for junction temperature if the traction network is shorted. Without going into a detailed description how this temperature is checked, we should note that the thermal resistance of rectifiers under transient conditions differ markedly from a steady-state thermal resistance.

Use of fans in protective units considerably decreases their reliability. In fact, the entire circuit of these units is based on static elements which do not contain any moving or rotating parts, and fans which must function day after day require proper service. When fans are interlocked to the control relay, the protective unit is turned off if the fan fails and the underground structure is subjected to the damaging effect of stray currents. Fan breakdown and the consequent turning off of the whole unit can be detected only by service personnel in 7-10 days. Therefore, it is good practice to abandon the use of fans and to use natural air cooling.

It appears that elimination of forced air cooling decreases many times the nominal current capacity in anticorrosion units. It is known, for example, that type BK2-200 diodes designed for 200 A current with forced air circulation of 10-12 m/sec can carry only 40 A current under natural cooling conditions. However, it has been shown in other studies that the air velocity at the heat sink is not zero when forced cooling is not used, as an air circulation is produced by natural convection. Using a rotary anemometer, it is possible to measure the velocity of the cooling air under natural cooling conditions. It is evident from the curves in Figure 19 that the air velocity of 2 m/sec decreases the thermal resistance of diode by 1.5 times, as compared with its value without the forced cooling (S = 0).

Let us calculate the maximum possible current in an UD-AKKh draining unit under steady state conditions without a fan (the unit is designed for a nominal current of 200 A). The circuit of this unit has four BK2-200 diodes.

The initial data are:

One-phase bridge circuit ($m = 2$)

$K_{c\ d} = 0.90$

$R_r = 0.69 \cdot 10^{-3}$ ohm

$U_{t\ r} = 1.02$ V

$A = 2.47$

$N_{par} = 1$

$K_{c\ res} = 1.1$

It was established that the velocity of cooling air was $V = 1.8$ m/sec when an average of 150 A flows through the draining unit.

At first we determine the total thermal resistance of BK2-200 diodes at $S = 1.8$ m/sec and $R_t = 0.65$ degree/W. By assuming that $\theta_0 = 40°C$ and $\theta_{(p-n)lg} = 120°C$ we find that

$$\Delta\theta_{(p-n)lg} = \theta_{(p-n)lg} - \theta_0 = 80°C$$

The value of $\theta_{(p-n)lg}$ is conservative, and an allowable value of $\theta_{(p-n)lg}$ is 140°C. The power losses in rectifiers under long-term steady state conditions can be found from expression (2-8):

$$\Delta P_{r\ al} = \frac{\Delta\theta_{(p-n)lg}}{R_t} = \frac{80}{0.65} = 123 \text{ W}$$

If known values are introduced into expression (2-10)

$$1.02\, I_{r\ al} + 2.47 \cdot 0.69 \cdot 10^{-3}\, I^2_{r\ al}$$

we obtain a quadratic equation with respect to the allowable average current in the rectifier. Solution of this equation results in $I_{r\ al} = 100$ A.

The allowable current which can flow through the draining unit for a long time when the fan is eliminated will be

$$I_{lg\ est} = \frac{mI_{r\ al}N_{par}K_{c\ d}}{K_{c\ res}} = 160 \text{ A}$$

If the air velocity is different than 1.8 m/sec when the fan is eliminated, the value of $I_{1g\ est}$ will be also different.

The thermal resistance R_{t2} can be lowered by the following means.

(a) In order to improve the heat emission properties of radiator, the surface of the heat sink should be painted with oil paint or coated with varnish. Experimental results obtained with hexagonal heat sinks of Silumin showed that black matte varnish increased the heat transfer with the surrounding air (V = 10 m/sec) by 14-19%, as compared with uncoated heat sinks. However, when rectifier heat sinks were placed close to each other, they screened the radiation and the increase in the heat transfer of coated heat sinks increased by only a few percent.

(b) It is desirable to have larger heat sink cooling surfaces. However, increasing the heat sink surface would not result in a proportional decrease of the thermal resistance of the rectifier. In the case of a hexagonal heat sink, it is impossible to have a different design. If the number of ribs in this type of heat sink is decreased, the distance between them will also decrease and this will lower the heat transfer, provided the volume and weight of the heat sink remains the same. The temperature at any point on the heat sink rib depends on the distance this point is from the base plate. With increasing distance the temperature drops, i.e., a temperature gradient exists between different heat sink points, leading to a poorer heat exchange.

Two standard heat sinks can be used per one semiconductor rectifier, provided the size of the whole unit allows it. In many cases this approach is acceptable, especially when the use of fans can be eliminated.

However, it must be kept in mind that doubling the cooling surface of the heat sink decreases the total external thermal resistance of the heat sink by only 20-30% (depending on the air velocity).

5. CONTACTLESS ELEMENTS OF CONTROL CIRCUITS

Silicon and germanium low power diodes, transistors, magnetic amplifiers, circuits of transistorized and combined magneto-transistorized preamplifiers belong to the contactless elements of the control circuits of automatic cathode stations and powered electric draining devices.

According to GOST 10862-64, all semiconductor devices are designated by four elements. The first element (letter or digit) designates the type of material, Г or 1 stands for germanium and K or 2 for silicon. The second element (letter) designates the class or group of devices, Д for universal or rectifying diodes, C for voltage stabilizing tubes, T for transistors, И for tunnel diodes, etc. The third element is a number which designates the use or electric properties of the device. Thus, low frequency rectifying diodes are designated by 102-399; universal diodes by 401-499; voltage stabilizing tubes of average power with the stabilizing voltage of 1-9.9 V by 401-499 and those with stabilizing voltage of 10-99 V by 501-599. Voltage stabilizing tubes of higher power and the above mentioned stabilizing voltages are designated by 701-799 and 801-899. The fourth element is a letter indicating the modification of a given device in a given group. For example, КД102А means the silicon rectifying diode, of A kind.

Devices designed prior to 1964 and which are still manufactured are designated by two or three elements. The first element is D for diodes, if for flat transistors. The second element indicates the applicability area of devices; 301-400 stands for flat germanium diodes, 201-300 for flat silicon diodes, 201-300 for high power low-frequency germanium transistors, 301-400 for high power low-frequency silicon transistors, and 801-900 stands for voltage stabilizing tubes.

The principle of function of diodes used in the control circuits of protective devices does not differ from that of the high power semiconductor rectifiers. Presently a great number of rectifying diodes are produced with different values of rectifying current, reverse voltage, and other parameters.

Table 7 presents the basic parameters of rectifying diodes used most frequently in control circuits of anticorrosion devices.

Table 7. Basic parameters of rectifying diodes

Types of Diodes	Nominal rectifying current	Maximum reverse voltage, V	Forward voltage drop, V not more than	Maximum reverse current at nominal voltage
Germanium fused diodes				
Type Д7А-Д7Ж	300 mA	25-400	0.5	100 μA
Silicon fused diodes				
Type Д202-Д205	400 mA	100-400	1	500 μA
Д206-Д212	100 mA	100-600	1	50 μA
Д242-Д248Б	5-10 A	50-200	1-1.5	3 mA
Germanium fused diodes				
Type Д302-Д305А	0.8-1 A	50-200	0.3-0.35	8-12 mA

The rectifying diodes perform realiably under all possible working temperatures of anticorrosion devices. Diodes, as a rule, are connected by soldering to other control circuit elements. It is important not to overheat the diodes during soldering. The soldering time for the majority of diodes should not exceed 3 sec, and the point of soldering should be not closer than 12 mm from the diode body. The diode lead can be bent at a distance of 3 mm from the body. While mounting diodes it is not recommended to apply much force.

Testing the volt-ampere characteristics of rectifying diodes is conducted according to the method described in section 1 of this chapter for power rectifiers.

Stabistors are a special group of silicon diodes used for the voltage stabilization.

A silicon single crystal contains higher concentrations of donor and acceptor impurities. Because of this an avalanche-type increase of the

reverse current takes place when a certain reverse voltage is applied to a stabistor. However, this process is reversible, i.e., when the reverse voltage decreases the reverse current returns to its initial value. The volt-ampere characteristic of the stabistor is shown in Figure 23a. The sharply increasing negative branch is the working section of the stabistor. This section is limited from above by the allowable minimum current value of the stabistor $I_{st\ min}$, and from below by an allowable maximum current value, $I_{st\ max}$, which is determined by the maximum power limit that is transformed into the heat in the stabistor.

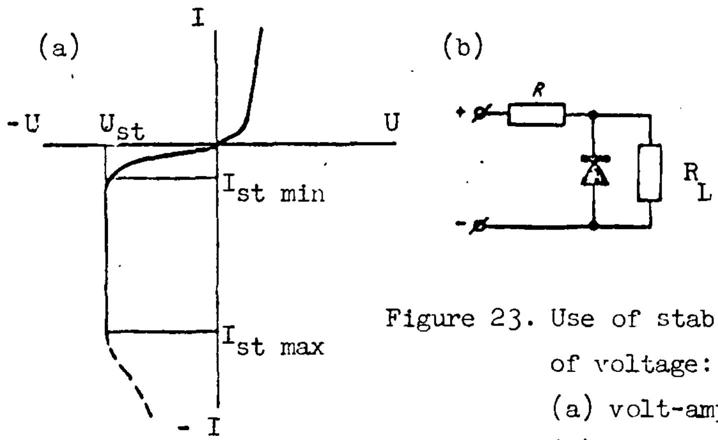


Figure 23. Use of stabistors for the stabilization of voltage:
(a) volt-ampere characteristic;
(b) connection diagram.

Figure 23b shows the connection diagram of the stabistor. When the input voltage I_{in} is changed, the current flowing through the stabistor also changes but the output voltage U_{out} remains practically unchanged.

Stabistors are used in automatic powered draining units and cathode stations in circuits which provide the reference voltage which is compared to the potential difference between the protected structure and the reference electrode. The stability of these circuits should be sufficiently high because the output of the protective unit depends directly on it when the value of stray currents changes.

The basic parameters of the stabistors are: U_{st} the stabistor voltage, $I_{st\ max}$ the maximum stabistor current, P_{al} the allowable stabistor energy

dissipation. According to U_{st} and P_{al}, stabistors are divided into low-voltage, high-voltage, and low power, average power and high power.

Table 8 presents basic properties of stabistors used in anticorrosion devices.

Table 8. Basic parameters of stabistors

Type of silicon stabistors	Nominal stabilization voltage	Stabilization current, mA		Maximum dissipation mW
		$I_{st\ min}$	$I_{st\ max}$	
Д806-Д813	7-14	3	20-33	70-280
Д814А-Д814Д	7-14	3	7.2-11.5	100-340
Д815И-Д817ГП	4.7-47	10-50	45-1400	5000-8000
Д818А-Д817Г	7.65-11.25	3	11	100

It should be remembered that the regulating polarity of the stabistor is reversed to the polarity indicated on its body.

Semiconductor transistors have found broad applications in circuits of automatic anticorrosion devices. Transistors, as a rule, are used in cascade circuits of the signal preamplifiers. The input signal is the difference in potential between the underground structure and the reference electrode, or the difference between a given value and the value set during adjustment of the stabilized reference voltage. In addition, transistors are used in the control circuits of thyristors.

The semiconductor triodes are made of single crystals of germanium or silicon which then are transformed into a three-layer structure by adding to them acceptor and donor impurities. Triodes possess the alternating conductance p - n - p (Figure 24a). In the structure of type p - n - p the initial single crystal has n conductance and the concentration of the acceptor impurity in outside layers exceeds 100-1000 times the concentration of the initial donor conductance. In transistors having the structure of type n - p - n the initial single crystal possesses the p conductance and the outside layers contain donor impurities.

One of the outside transistor layers is the emitter, the other is the collector, and the middle layer is the base. Emitter and collector can

be considered as the power electrodes, and the base the control electrode. The transistors with n - p - n and p - n - p structures have two p-n junctions. The action of these junctions can be considered to be independent in transistors. Transitions Π_1 and Π_2 which originate during the formation of three-layer structure have the same physical nature as p-n junction in diodes (see section 1 of this chapter). The transition Π_1 between emitter and base is called the emitter transition, and the transition Π_2 between base and collector is the collector transition.

When the external voltage source is absent, blocking layers with a potential barrier originate in the emitter and collector transitions as in the p-n diode junction. Opposite currents of basic and secondary current carriers pass through the transitions Π_1 and Π_2, and in this case balance each other.

In the case of p - n - p transistors, a diffusion of holes takes place from left to right through the Π_1 transition. Electrons, the basic current carriers of the base move from right to left through the same transition. The secondary current carriers (holes in n-layer and electrons in p-layer), which are accelerated by an electron field formed in the p-n junction, simultaneously produce the so-called drift currents. The hole drift current comes from the n into the p layer, and the electron drift current from the p into the n layer. The direction of the drift current correspond to the opposite direction of the diffusion current. When the external field is absent, i.e., the external voltage source, the diffusion and drift currents of each type of carriers are equal and the resulting current which passes through the Π_1 transition is equal to zero.

The primary and secondary current carriers move similarly in the Π_2 transition. The total current of this transition is also equal to zero.

If external sources of constant voltage are supplied a type p - n - p triode in such a manner as to create a positive potential $+U_e$ on emitter E and a negative potential $-U_c$ on collector C with respect to the base, the potential barriers of transitions Π_1 and Π_2 will be significantly changed. The potential barrier in the emitter transition will decrease in value by U_e, and in the collector transition it will increase by $-U_c$.

A decrease of the potential barrier of the emitter transition increases the diffusion current value, holes will move from emitter to base

and electrons from base to emitter. Due to the fact that the concentration of holes in the emitter is 100-1000 times higher than the concentration of electrons in the base, the major part of the electron current I_e is carried by holes. The injected holes continue their motion in the base, part of them recombine with electrons which move from base to emitter and the remaining holes approach the collector transition. As a result the holes pass over the potential barrier Π_2 and produce the collector current I_c.

New electrons from the external source replace the recombined electrons and the current I_b is formed in the base circuit. Under ordinary conditions the base current amounts to a small fraction (1-5%) of the emitter current.

There are three possible ways to use the semiconductor triode in cascade amplifier circuits: either with a common base, emitter, or collector.

The first variation introduces the input signal (circuit input) into the emitter circuit and requires a resistance load between the collector and base. The base serves in this case as the common electrode for the circuit of input signal and load, and therefore this variation is called the common base connection. We can not get current amplification in this circuit because the collector current is always smaller than the emitter current. Therefore the amplification of power can be secured only by the increase in voltage and it is relatively small.

The second variation allows amplification of both the current and voltage and consequently has considerable power amplification. The input signal in this case is applied between the base and emitter and the load resistance is located between the emitter and collector. Emitter in this case serves as the common electrode for the input and output circuit.

The third variation has the load resistance in the emitter section of the circuit. The collector serves as the common electrode. This circuit provides for the amplification of current and of power, with no voltage amplification. This variation is often called an emitter follower because the output voltage has a value which differs little from the input signal.

In all three variations of the triode connections, the voltage change in the emitter transition in fact controls the value of input and output currents.

The control function of the base electrode is accomplished by changing the number of carriers present in the base. When electrons, which are carried to the base of the p - n - p triode, induce a negative potential in the base with respect to emitter, the flow of holes through the emitter transition increases. The collector current also simultaneously increases because of the concentration gradient increase of the carriers in the base.

Transistors have input and output static volt-ampere characteristics. Figure 25 shows, for example, the input and output characteristics of a transistor connected with a common emitter. The input characteristics shows the relation between input currents (base current for give circuit) and the base-emitter voltage at fixed collector to emitter voltages (see Figure 17a). These characteristics resemble the volt-ampere characteristics of semiconductor diodes. The current in this case sharply increases with voltage. The output characteristics show the dependence of the collector current on the voltage between collector and emitter with a fixed value of the base current.

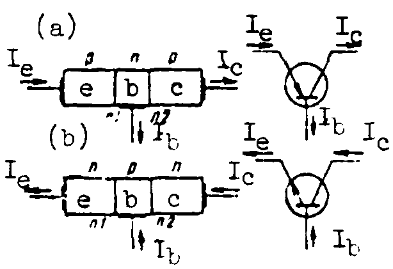


Figure 24. Structural diagram and designations of transistors:
(a) - type p - n - p;
(b) - type n - p - n.

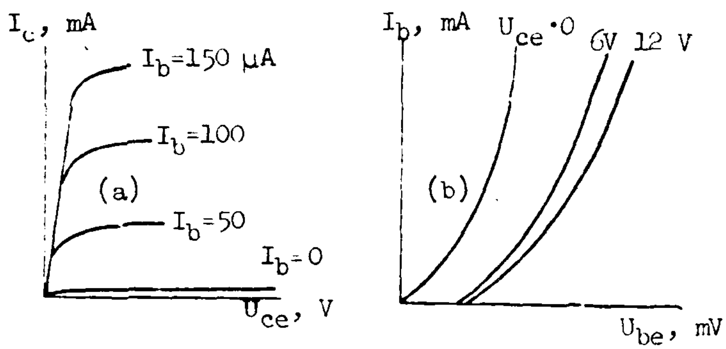


Figure 25. Characteristics of a transistor connected to a common emitter;
(a) input;
(b) output.

The volt-ampere characteristics of transistors are tested with DC by point to point measurements, or with the use of special testing devices called curve tracers.

DC small signal parameters are of importance for transistors used in anticorrosion devices.

The DC parameters characterize the value of leakage currents flowing through the transistor. These parameters and their dependence on temperature are used to calculate the transistor DC bias voltages and operating point stability. The DC parameters are:

$I_{c\ rev}$, the reverse current of the collector transition when the emitter is disconnected and at a given collector to base voltage.

$I_{e\ rev}$, the reverse current of the emitter transition when the collector is disconnected at a given emitter-base voltage.

$I_{c\ in}$, the collector initial current, the current in the collector circuit when emitter and base are closed and a given voltage is present in the collector.

$I_{c\ c}$ is the collector current of non-conducting transistor, the collector current when the emitter transition is reverse biased and a given voltage is present between emitter and collector.

The relation between the alternating voltages and currents at the input and output of the transistor is represented by a linear four-terminal network. The system of h parameters is the most widely used. The equation of a four-terminal network in this case is

$$\begin{aligned} U_1 &= h_{11}I_1 + h_{12}U_2; \\ I_2 &= h_{21}I_1 + h_{22}U_2 \end{aligned} \qquad (3\text{-}2)$$

where U_1, I_1 and U_2, I_2 are voltages and currents at input and output of the four-terminal network, respectively.

If we create the short-circuit condition with respect to AC at $U_2 = 0$ or at $I_1 = 0$, the following definitions of h parameters can be given:

(a) The input resistance h_{11} is the ratio of input voltage to input current changes produced by it (at $U_2 = 0$);

(b) The voltage feedback coefficient h_{12} is the ratio of the voltage change at input to the increased output voltage produced by it (at $I_1 = 0$);

(c) The output conductance h_{22} is the ratio of output current change to the change of output voltage produced by it (at $I_1 = 0$);

(d) The amplification coefficient with respect to current h_{21} is ratio of the output current change to increasing value of the input current caused by it when the output circuit is shorted.

These transistor parameters are determined by electric measurements. A detailed method of measurement of $I_{c\ rev}$, $I_{e\ rev}$, $I_{c\ in}$, $I_{c\ c}$, h_{11}, h_{12}, h_{22} and h_{21} is presented in GOST 10864-64, GOST 10867-64, GOST 10865-64, GOST 10866-64, GOST 10868-64, GOST 10869-64, GOST 10871-64 and GOST 10870-64, respectively.

The value of thermal resistance should be known for intermediate and high power transistors to calculate the heating effects.

Table 9 presents basic functional parameters of transistors used in circuits of automatic anticorrosion devices.

During the mounting and adjustment of high power transistors, the base lead should be connected to the circuit first.

It has been mentioned before that transistorized DC amplifiers are used in circuits of automatic cathode stations and powered electric draining units. The main feature of these amplifiers is a direct connection between stages without the use of capacitors and inductors. With these type of the cascaded stages, not only the useful signal passes through the amplifier but also unwanted fluctuations which are present because of the instability of current sources, changes of the circuit electrical parameters, and outside interference.

These fluctuations contain an alternating and constant components, and this leads to additional changes of the instantaneous values of the output voltage and current with respect to time. Fluctuations appear not only in the presence of a useful signal but also in its absence. In this case they characterize the time-related drift of the amplifier.

The time-related drift in transistorized amplifiers is determined mainly by the output voltage instability caused by changes in the temperature environment. Changes in the output voltage that occur during a definite time interval, with a constant value of the input signal, indicates the value of resulting drift.

The introduction of emitter resistances is one of the basic methods to stabilize the temperature effects of transistorized amplifiers. The lower

Table 9. Basic funtional parameters of transistors

Transistors	Maximum collector current, A	Maximum current of the base, A	Maximum voltage, V			Dissipation power, W
			Collector -base	Collector -emitter	Emitter -base	
Germanium fused low frequency low power						
МП39-МП41А	0.15	--	10	10	11	0.15
Silicon fused low frequency low power						
МП111-МП113А	0.02	--	20	20	5	0.15
Germanium fused intermediate frequency intermediate power						
ГТ403А-ГТ403И	1.25	0.4	45-80	30-60	20	--
Germanium fused low frequency high power:						
П210Б, П210В	12	--	65	40	25	45
П213-П215	5	0.5	45-60	30-60	10-15	--
П216Б-П217Г	7.5	0.75	35-60	35-60	15	24
Silicon fused low frequency high power						
П302-П306А	0.5	0.2	35-60	35-80	--	7-10

the resulting voltage in the base circuit and the higher the resistance in the emitter circuit, the lessor the effect of the temperature drift because the emitter transition participates relatively less in the increase of the thermal component of the collector current.

The temperature drift can be lessened by an appropriate selection of the transistor biasing circuit in subsequent stages of the amplifier. If the thermal flux of the collector circuit of the next stage has a direction which is opposite to the thermal flux of the preceeded cascade, the total thermal drift of the amplifier significantly decreases. This approach is possible in circuits where transistors are connected in the common emitter configuration.

If it is necessary to almost completely eliminate the temperature drift, more complex thermal compensation circuits are used. This requires inclusion of a temperature sensitive element in the cascaded circuit. The resistance of this element, as a function of temperature, should change in such a way as to produce a complete compensation of the thermal component of collector current. In many instances a semiconductor diode connected in the non-conducting direction can be used as a temperature-dependent resistance. With increasing temperature the reverse diode resistance decreases. The use of a semiconductor resistance with a negative temperature coefficient, i.e., thyristor, as a thermal compensating element is advisable. The temperature-compensating elements should be selected for each individual amplifier. This makes it difficult to interchange the circuit elements. Because of this, balanced semiconductor stages are used in multistage amplifiers where the drift currents in the two amplifier channels are equal in value but opposite in direction (with respect to the output circuit).

The output power of the transistorized amplifier, and consequently the selection of transistor of this stage, is determined by the power necessary in the amplifier load. Control circuits of thyristors, magnetization windings of magnetic amplifiers, and saturation chokes can serve as output circuits for transistorized amplifiers in automatic anticorrosion devices.

Magnetic amplifiers and saturation chokes can be considered as controllable inductive resistances connected in the AC line. The inductive resistance of magnetic amplifiers can be changed by producing a constant magnetic flux in the magnetic circuit of the amplifier. The unit under

consideration has power windings in the AC line and control windings (magnetization) in the DC line.

When the magnetic amplifier is on, the alternating magnetic field produced by the AC load winding is added to a constant magnetic field produced by the control winding. The resulting magnetic induction exceeds the saturation induction of the core during a definite time period. The magnetic permeability of ferromagnetic core decreases following the bend of the magnetization curve. This leads to a decrease of inductive resistance of the amplifier power windings. Current in the power winding circuit depends on the input voltage the resistance of the load circuit and the resistance of the amplifier power windings. The inductive resistance of the choke power windings exceeds considerably the external load resistance, and the magnetic permeability of the core material is low when the magnetic amplifier operates under saturated conditions. The increased resistance of the amplifier windings decreases the current in the AC circuit.

The magnetic amplifier operates under saturated conditions for only a definite part of the AC period. The higher the magnetization current of the field produced by the control windings, the longer the time the magnetic amplifier operates under saturated conditions and the higher will be the average current flowing through amplifier power windings and external load. Thus, the current in the main circuit can be controlled by changing the magnetization current.

If semiconductor diodes are connected at the magnetic amplifier output, half-waves of rectified current will pass through the amplifier power windings. In this way an additional self-magnetization effect is produced. It is thus possible to select the parameters of the magnetic amplifier so that it will operate under saturated conditions due only to self-magnetization when the current in control windings is absent. In this case the inductive resistance of the amplifier will also be minimal. This resistance can be increased by producing an negative field in the control winding which switches the magnetic amplifier into the zone where the inductive resistance of the amplifier power windings sharply increases before the magnetic circuit reaches saturation. Internal feedback is produced by connecting the power windings in series with the rectifying diodes.

The design of magnetic amplifiers makes it possible to use another external winding. In this case an additional winding, the feedback winding, is connected in the amplifier output circuit in series with load after the rectifier. Figure 26 shows such an amplifier design. Windings of the main circuit W_H are located on outside legs of the Ш -shaped core in this type of amplifier, and the control W_c and feedback W_f findings are arranged in the center. In some cases, additional windings, the displacement windings, through which DC is passed are used.

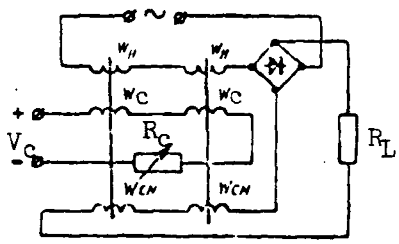


Figure 26. Circuit of magnetic amplifier with external feedback connection.

In those cases when it is impossible to achieve the necessary amplification with a one-stage magnetic amplifier, two or more cascaded stages are used. For example, two stages are used in the TK-4 unit for controlling the potentials of the draining points of the tramway line.

Magnetic amplifiers do not always provide high DC stability. The offset distortion of amplifiers can be the result of aging of materials from which the amplifier elements are made, the voltage and frequency of the supply line, presence of external magnetic fields, etc. The most effective method to increase the offset stability is by the use of dual balanced amplifier circuits.

In many instances transistorized-magnetic amplifiers are used in various types of automatic anticorrosion devices. The combined performance of magnetic and transistorized amplifiers very often eliminate shortcomings inherent in many types of amplifiers and to fully use their capabilities. This approach decreases the weight and size of amplifiers, and improves their performance characteristics.

Figure 27 shows the circuit of the transistor-magnetic amplifier of the TK-4 unit. It consists of two cascaded transistor stages and two cascaded magnetic amplifier stages. The signal is received by transistor T_1, the collector current of which flows through the emitter - base of the transistor T_2. Transistorized amplifier stages have a common emitter fed from a

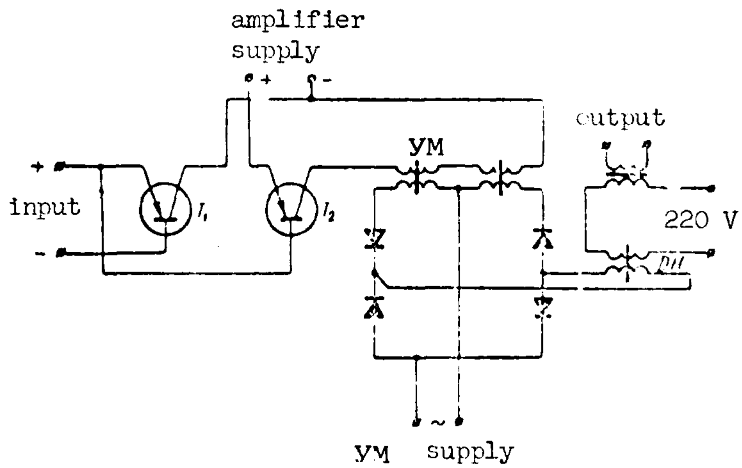


Figure 27. Magnetic amplifier of the TK-4 unit.

rectifier block. The control winding of the intermediate magnetic amplifier MA serves as a load for the collector circuit of transistor T_2. The output current in this chain changes from 0.8 to 220 mA, depending on the value of received signal.

The AC winding of УМ is connected with the control windings of the power saturation choke ДН through the rectifiers. The signal change at the amplifier input produces changes in the inductive resistance of ДН and as a result changes the voltage in the primary winding of the power transformer.

Extensive use of thyristors has significantly limited the area of application of magnetic amplifiers because thyristor control has several advantages compared to magnetic amplifiers (lower power in control circuits, smaller size, lower cost, etc.). It can be expected that newer types of anticorrosion devices with automatic control will be designed without magnetic amplifiers.

6. CONTACTORS AND RELAYS

Relays and contactors which provide the closing of the draining circuit upon reaching the required polarity difference between the underground structure and a rail are widely used. Polarized electrodraining units can use either relay-contactor devices or a combination of switching relays and power semiconductor diodes. The use of relays in these cases increases the sensitivity of the draining circuit, as compared with a circuit with only the semiconductor diodes. Circuits of powered draining units and cathode stations where forced-air circulation is required over diode and thyristor blocks must switch off the supply line contactor if the blower stops operating.

Our industry presently produces more than 300 types of electromagnetic relays and contactors which differ in design, size and electrical characteristics. Some of these types have a great number of variations, with different numbers and sizes of windings, design and total number of contacts, time characteristics, etc. The type and an actual design of a relay or contactor is selected according to technical requirements, considering the current, voltage and operation conditions.

The electromagnetic relays and contactors have a receiving element (coil) that responds to the input current and executive elements (contacts) which control the output current. The electromagnetic relays are classified according to type of current (DC or AC), number of windings (single winding, multiple-winding), number and type of contacts, and manner of armature motion [8].

The condition of the contacts should be closely watched when contactors and relays are used in electric apparatus. In order to insure a reliable circuit closing the contacts should be adjusted to have a so-called "cave-in" of the movable contact when it contacts the stationary contact, i.e., a wiping of the movable contact against the stationary contact. The contact cave-in determines the contact point thickness and its wear during operation.

During the closure of both the movable and stationary contacts, surface oxide films are destroyed because of a constant pressure of the contact spring. This lowers the contact resistance and in general improves the performance.

Contacts are replaced regularly after the wear reaches noticeable proportions. The electric wear-resistance of contacts amounts to only 10% of the mechanical wear-resistance of the entire contact.

Contactors can be selected according to their heating properties given in Table 10.

Table 10. Allowable heating of contactor elements

Name of current-conducting elements		Allowable heating temperature, ^{o}C
Coil with insulation of class:	A	120
	E	130
	B	140
Main contacts with copper contact points		105
Block-contacts with silver contact points		120
Flexible copper connections		105
Binding posts for external leads with rubber or polychlorovinyl insulation		95

The coil insulation is classified according to GOST-8865-58.

The presence of contact devices complicates the work of anticorrosion units. The inclusion of thyristors in the primary transformer network make it possible to completely exclude the use of contact devices. In the case of short circuits, the voltage is removed from a circuit by the thyristors.

CHAPTER 3

INSTALLATION, ADJUSTMENT AND TESTING OF ELECTROPROTECTIVE DEVICES

1. POWERED AUTOMATIC DRAINING UNIT TYPE UD-AKKh

The powered automatic draining unit of type UD-AKKh is installed on a foundation 0.4 - 0.5 m high above the soil surface (Figure 28).

The installation can be divided into the following stages:

(1) The cabinet is bolted to foundation in such a way as not to deviate from the vertical line by more than 2^{o}.

(2) The negative lead of the rectifier (center tap of the power transformer secondary winding) is connected to the protected underground structure, using for this purpose a cable with a cross-section calculated for the protected structure. An identical cable is used for connecting the positive lead of the power rectifier to a rail through a 300 A = 75 mV shunt.

(3) Insulated twin cables 1.5 mm^2 in cross-section (with respect to copper) connects the control device (CD) on the protected structure with the draining unit signal circuit. One conductor of this cable is connected between the structure and the plug connector (ШР) 25ШР of the control block (negative pole of the signal circuit, Figure 30); the second conductor connects the reference electrode with 24 ШР (positive pole of the signal circuit). A nonpolarizable long-lasting electrode, or tubular grounding electrode, should be used for reference electrodes. The latter should be placed in the vicinity of CD in such a way as to make its end 150-200 mm below the soil freezing level.

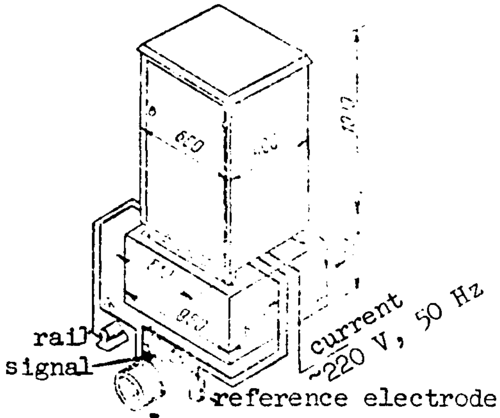


Figure 28. Automatic draining unit type UD-AKKh (installation drawing).

(4) The power supply cable from a single-phase 220 V AC source to the draining unit should be installed according to rules presented in PUE. An insulated cable or twin copper cable 100 mm^2 in cross-section should be used to connect to the power supply source. The case of the automatic draining unit must be connected to the protected groun' according to PUE. It is of importance to keep moisture and dirt out of the draining unit during its installation.

<u>Testing and Adjustment of the Electrodraining Unit</u>. Jumpers should be attached to the power transformer secondary winding according to the output voltage (6 or 12 V) before the draining unit is turned on. All draining units are manufactured for 6 V DC (Figure 29). When it is necessary to work with 12 V DC, jumpers between terminals 1 - 4, 2 - 3, 4 - 6, and 6 - 7 are removed and installed between terminals 1 - 2 and 5 - 6. Before trial the feedback of the draining unit is turned off with the switch B_2 (see schematic diagram of UD-AKKh draining unit), or the fuse Π_4 is removed. After the electrodraining unit is turned on with the rotary switch ПB and the feed toggle switch is

closed, the presence of voltage in the circuits of the transistor amplifier is indicated by the neon bulb ЛС.

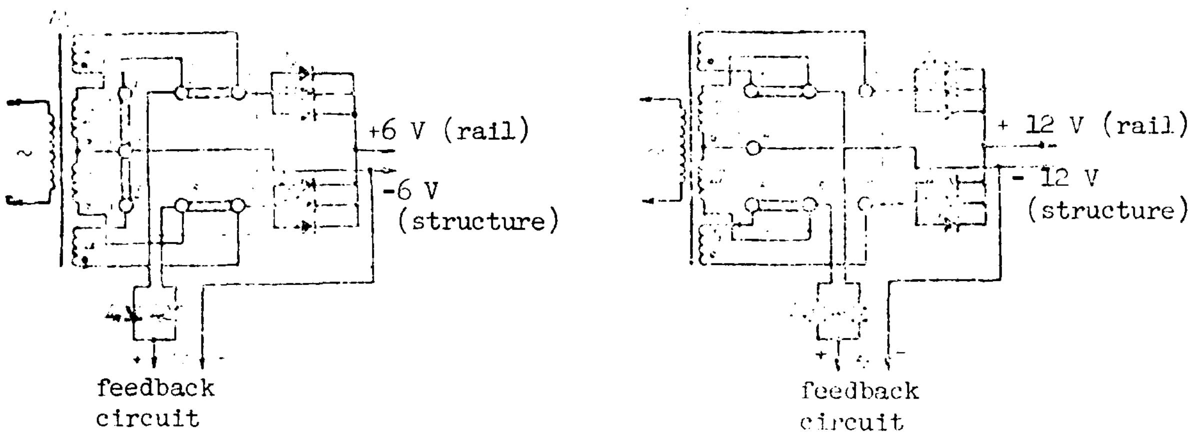


Figure 29. Switching circuit of the transformer secondary winding of powered draining unit type UD-AKKh.

Prior to adjustment of the required working conditions of the draining unit, the performance of the automatic control circuit should be checked first. This is accomplished by temporarily switching off the reference electrode and the protected structure (terminals 24-25, Figure 30) from the control block input. Then a DC voltage, which is controllable within the range of 0-1.5 V, is supplied to terminals marked "Signal", observing the polarity. The voltage divider, a potentiometer with a 0.1-1 kohm resistance range, galvanic cell type 332 (FBS-0.25), etc., can be used for this purpose. After finding the control block functioning properly, the DC source is disconnected from the "Signal" terminals and the cable from the reference electrode and underground structure is connected to them.

Next, the required protective potential value on the protected structure is adjusted with the potentiometer R_1. If this potential is low when the draining unit is turned on and the output voltage of the power rectifier is nominal, the feedback circuit of the magnetic amplifier УМ is switched on. This is accomplished by putting back the safety fuse $П_4$ and closing the circuit with the switch B_3.

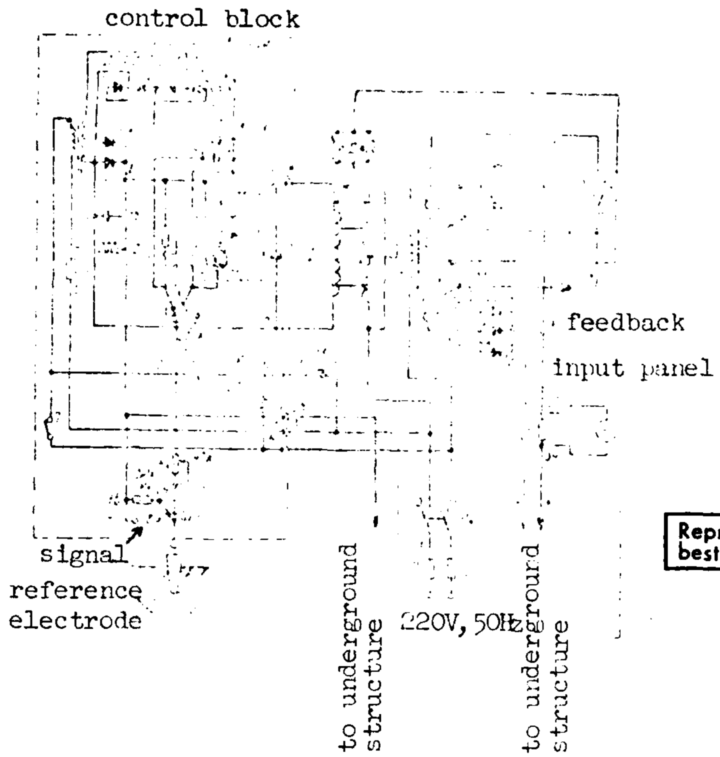


Figure 30. Basic schematic circuit of the powered draining unit type UD-AKKh.

Figure 31 shows a general switching circuit of checking and supplementary devices which are used during a general trial and adjustment of the draining unit before switching it on.

In order to increase the efficiency of the draining unit, it is sometimes necessary to change the hookup of the amplifier windings in addition to the feedback circuit of УМ. Figure 32 shows possible variations of the interconnection of these windings to accommodate the various values of a load resistance at the unit output. Different suggestions are provided below on the use of the feedback circuit under different operating conditions of the unit (primarily under high currents).

Changing the magnetic amplifier windings should be accomplished after removal of protective fuses Π_2 and Π_3 and opening the rotary switch (Figure 30). It should be kept in mind that dangerous voltages can be present in the control windings of magnetic amplifier when its working windings are incorrectly connected. Therefore, if any changes of УМ windings were

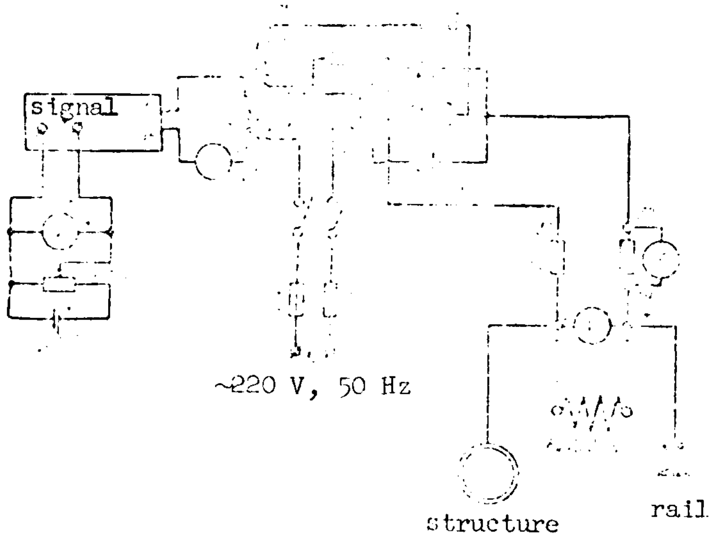


Figure 31. Connecting digram of measuring instruments during checking and adjustment of the powered draining unit type UD-AKKh.

attempted before, the draining unit should be turned on only when the plug connector ШР is disconnected and the AC voltage in the winding I is watched closely. This voltage should not exceed 5 V when the windings are correctly connected. The draining unit can be put into operation only after the above procedures are followed.

A complete check of all components of the УПТ circuit according to the schematic diagram shown in Figure 30 should be performed after breakdown or repair of the control block of the UD-AKKh unit.

Let us consider in detail the performance of the transistor DC amplifier of УПТ, with a control signal at its input coming from the protected structure and from the reference electrode

A total voltage consisting of the reference voltage and of the measured protective potential (error signal) acts at the input emitter-base circuit through resistor R_3.

The blocking voltage at the amplifier input is produced automatically due to the voltage drop in resistor R_1 which is present in the emitter

circuit of transistors T_2 and T_3. Variable resistor R_1 sets up the required potential which is maintained on a structure and which causes transistor T_3 to conduct. The circuit provides the required potential and automatically maintains it on the underground pipeline within 0.5-1.5 V.

A separate stabilized bridge rectifier consisting of four semiconductor diodes D_3-D_6 biases the first two stages of the transistor amplifier (transistors T_3 and T_2). Stabistor D808 (D_7) in series with resistor R_4 stabilize the rectified voltage.

The rectifier is fed from the secondary winding of the small power transformer TP_1. The rectifier should provide a stabilized voltage within 7.5-8 V when the current is equal to 25 mA. The rectifier output voltage stability after adjustment should not be below 0.1%. A separate full wave rectifier, diodes D_1 and D_2, fed from the third transformer winding of TP_1 is used to bias the third (output) stage, transistor T_1, of УПТ . This rectifier should provide an output voltage of 30-25 V with up to 1 A of current.

The negative lead of the rectified voltage (center tap of winding III of TP_1) is connected to the transistor T_1 collector through the control УМ winding I of УМ which serves as the collector load of the output stage of УПТ. In order to prevent the self-excitation of УПТ at ultralow frequencies, a damping capacitor C_3 is connected in parallel with winding I of .

A decrease in the potential on a structure leads to an unbalance between the reference voltage (which is established by variable resistor R_1) and the potential on the structure as determined by the reference electrode. The error signal is amplified by transistor T_3 because of the collector current change (averaging from 300-350 to 450-500 μA). The voltage drop across resistor R_2 in the base of transistor T_2 also changes its collector current. The collector current of T_2 decreases from 25-20 to 15-12 mA. A drop in the collector current of T_2 and of the voltage across R_3 sharply increases the negative potential of the transistor T_1 base (from 100-150 mV to 1.5-2 V). As a result, transistor T_1 saturates and the collector load current (1УМ winding) sharply increases (from 5-10 to 700-800 mA). Magnetic amplifiers of type УМ1П -40-56-51 which contain eight windings is modified to some extent before being installed into the automatic draining unit. This is accomplished by adding one control winding connected in series to the four existing control windings, and two feedback windings which are

connected in parallel and are fed from a small recitifier containing rectifiers D_{11} and D_{15} (Figure 30). The total DC resistance of the series connected control windings of УМ (collector load of T_1) is within 40-42 ohms.

When an error signal appears at the УПП input, corresponding changes of the magnetization current that flows in the УМ control windings take place, as well as the reactive resistance of the УПП load windings. These windings control the voltage feeding the circuit transformer TP_2 which contains the rectifier unit (rectifiers D_8-D_{13}) which supplies power to the draining cable. Since the voltage flowing through the primary winding I of power transformer TP_2 is controlled, the voltage at the unit output changes and restores the protective potential on the structure.

A rotary switch ПВ and a toggle switch in the supply line of УПТ are provided for turning on the unit. The push-button switch, which is located in the cabinet door, switches on the bulb ЛО which shows the presence of voltage at the output of TP_1 and TP_2.

As opposed to earlier models of UD-AKKh, the standardized unit of type UD-AKKh uses a full wave rectifier circuit with a center tap. The power rectifier is an assembly of six silicon rectifiers, BK-200 (three rectifiers in each arm connected in parallel). All rectifiers are provided with finned heat sinks which are installed in the lower part of the cabinet by means of a common rail and angled elbows. The use of a large number of rectifiers BK-200 in the rectifying unit made it possible to exclude fans, magnetic starters and relays and to use natural cooling. This simplified the draining unit circuit, decreased maintenance cost and improved the reliability of the whole protective unit.

The feedback circuit is supplied with power from two type D-242 rectifiers (D_{14} and D_{15}) connected to a section of the secondary TP_2 winding. In Figure 30 the connection of leads of the secondary TP_2 windings corresponds to the output voltage of 12 V. If it is required to rearrange the leads of the secondary windings of this transformer, diodes D_{14} and D_{15} cannot be reconnected from terminals 36 and 38 to 35 and 39, otherwise maximum voltage will be applied across them (which would flow from all sections of the TP_2 secondary winding) and thermal breakdown of these diodes would destroy the feedback windings of УМ. Figure 29 shows the switching diagram and the jumpers of the secondary windings of TP_2.

If all subassemblies of the unit are in order, the performance is tried with an equivalent load.

Figure 31 shows the order of switching different devices and supplementary units when the entire unit is checked and adjusted. The DC voltmeter F_1 with a scale of 0 - 3 V measures the signal voltage at the control block output; the ammeter A_1 with a scale 0 - 1 A is needed for checking the current in the control winding of УМ . The ammeter is connected in the circuit between УПТ and УМ by attaching the negative terminal of A_1 to lead 18 (first disconnecting it from the УМ block) and the positive terminal to terminal 27 of УМ. The second DC voltmeter V_2, with a scale 0 - 15 V, is used to measure the voltage at the unit output (it is connected to terminals on the structure and rail).

If it is necessary to completely check the complete draining unit before installation at a required site, a suitable resistance (R_l = 0.02 - 0.1 ohm), capable of operating with a current up to 250 A, can be connected to the same terminals by flexible cables (100-150 mm^2 cross-section).

Two voltmeters of type M-231 are used for measuring the input and output voltage of the draining unit. They also can be used for measuring the output voltage of УПТ.

Before checking and adjusting the control block, the adjusting knobs of variable resistors R_1 and R_6 (Figure 30 and 31) are moved to the position of minimum resistance, and by varying potentiometer R_1 the zero reading of the voltmeter is achieved.

Then, by closing the rotary switch ПВ and the toggle switch of the control block supply, the presence of current at the УПТ output of the power amplifier unit (ammeters A_1 and A_2) is checked. The output current of working УПТ could reach 0.7 - 0.8 A. The current value at the unit output is determined by the parameters of the draining network (or by load resistance R_L) and by the switching circuit of the secondary TP_2 windings (6 or 12 V).

If the unit power block is operative, the control circuit is checked next. By watching the readings of the control instruments, the control block input voltage is gradually increased. The output voltage of УПТ should rapidly decrease and increase (from 0.7 - 0.8 A to 10 - 20 mA) when the input voltage is varied within 0.2 - 0.3 V with R_1. By repeating this procedure several times, the lower limit of the protective potential of the electro-

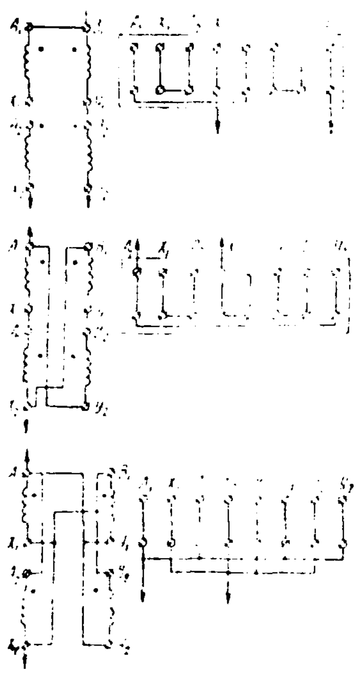


Figure 32. Connection diagram of working windings of the magnetic amplifier of the powered draining unit type UD-AKKh.

draining unit is established with the voltmeter V_1. The increasing rate of draining output current is established simultaneously by lowering the protective potential. This can be accomplished by increasing the resistance of variable resistor R_6 ("sensitivity") and by changing rapidly several times the output voltage (using R_1) at each new position of the resistor knob (Figure 31). This procedures is necessary to see how the increase in the output voltage of the signal circuit influences the unit output current when the protective potential is lowered. If the control circuit performs normally, the maximum increase of the unit output current should be obtained when the signal voltage at the control block output decreases by 75-100 mV with respect to the threshold value of the protective potential. The knob controlling the sensitivity of УПТ (R_6) should be located in the central position.

After all these procedures are performed, the signal at the control block output is gradually increased, as well as the reference voltage on

transistors T_2 and T_3 (by resistor R_1). At the same time, the set-up for different protective potentials and the upper control limit are checked.

Thereafter switch B_3 is closed (after installing the fuse Π_4), current is fed into the feedback of УМ and while watching the output current increase in the draining circuit (or in resistance R_L) the operating condition of the feedback circuit of УМ is checked.

2. POWERED AUTOMATIC DRAINING UNIT TYPE DUT-AKKh WITH THYRISTORS

The powered automatic draining unit type DUT-AKKh is installed on foundation similar to that of the UD-AKKh unit (Figure 28). All recommendations regarding assembly and installation of the UD-AKKh unit pertain to the DUT-AKKh unit.

The unit frame must be grounded according to PUE. There is a special bolt on one of the frame rails for grounding.

All elements and blocks of this unit are fixed on the welded frame made of angle steel which rests on rails. The frame with its assembled elements is located in a cabinet made of sheet metal. Four bolts are used to fix the cabinet to the frame. The cabinet is equipped with a door having a lock.

All individual elements are assembled in subassemblies and fixed to the frame. Monitoring and control devices are located on a panel made of sheet steel. In the upper left part of this panel there is an ammeter, the watt meter is located in the center, and voltmeter in the right-hand corner. Below the ammeter there is a fuse for the whole draining unit and a shunt. This fuse can be reached through a special opening covered with plexiglass. A plate with fuses and the radiointerference filter is fixed below the electric meter on the back side of the panel. Next to this plate there is a rotary switch. The handle of the rotary switch and heads of fuses are accessible from the front side of the panel. An opening for a recorder is provided at the right-hand part of the panel which is covered by plexiglass.

The terminal board of textolite is located below the instrument panel. It contains terminals for the rectifier (two terminals 8 mm in diameter), signal leads, supply voltage and a plug connector for a soldering iron or for powering the automatic recorder. A power transformer is located

on the back of the terminal board. Jumpers are also located on the terminal board and they are used for switching the transformer windings.

The thyristor block is attached next to the transformer in the frame corner. It consists of a textolite board with two copper heat radiators arranged one over another. Between radiators is capacitor C_8 (Figure 33) and resistor R_{53}

A terminal block for attaching the leads is provided on this board. In order not to damage the thyristors during installation of the recording unit, the thyristor block is separated from the recorder aperture by a removable plexiglass divider.

The power rectifier block consisting of six type BK-200 diodes is installed at the unit base. The diodes are mounted in such a way as to make replacement easy by pulling them from the heat sinks and disconnecting from the rail.

The electronic block is located above the instrument panel in a flat sliding metal box.

The control handles, warning lights, switch and a fuse are located on the front panel of the electronic block.

Handles for the removal of the block and fixing screws are located along the panel edges. The plug connector to connect the block with the circuit is located at the back side of the box. All block elements are divided into functional groups, each of which is mounted on laminated bakelite insulation which is attached to lugs in the lower part of the block. The complete block is covered by a plexiglass.

An illuminating bulb is located at the upper rail of the cabinet and it turns on automatically when the cabinet door is opened. Under normal operating conditions all control and signal elements are easily accessible when the cabinet door is opened. It is necessary to remove the cabinet when the transformer windings must be switched.

The circuit diagram is pasted on the back side of the door. There is also place for a maintenance and operation log.

Figure 33 shows the circuit diagram of the DUT-AKKh unit.

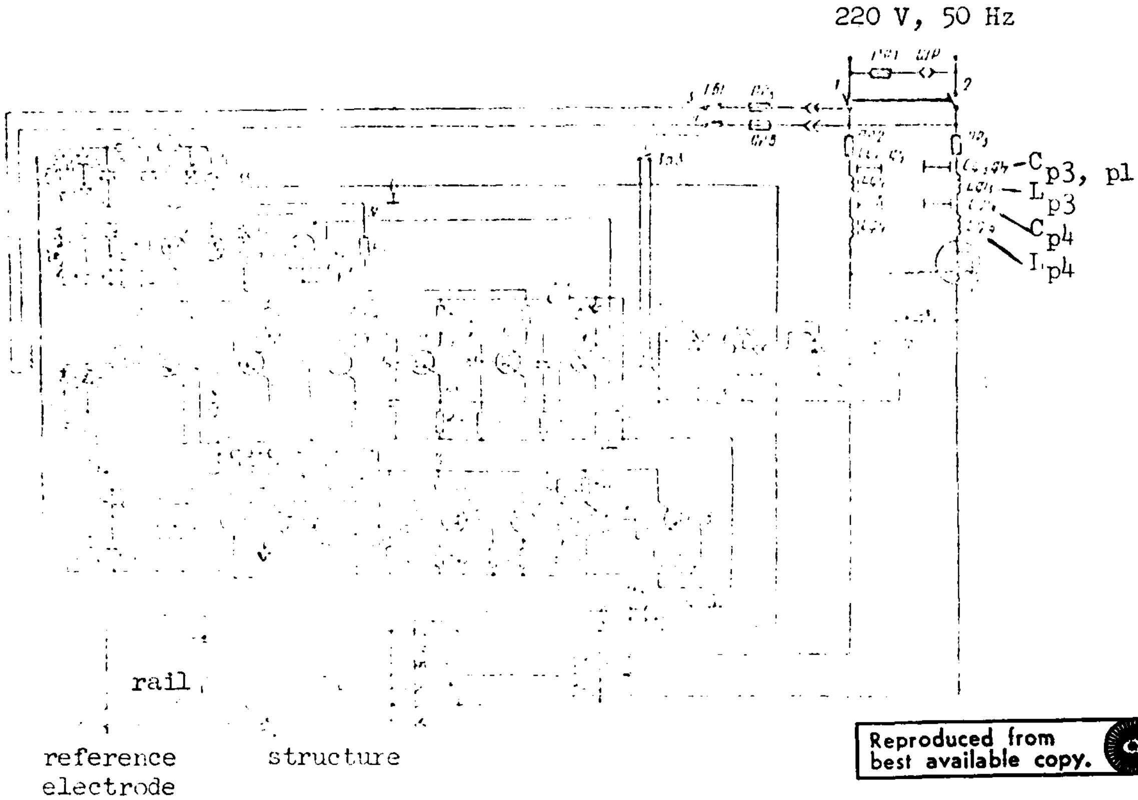


Figure 33. Circuit diagram of the powered draining unit type DUT-AKKh.

The DC output voltage flows to the rail (plus) and to the protected structure (minus) from the power rectifier ($ДС_1$-$ДС_6$). The power rectifier output voltage is controlled by the thyristor block ($ДУ_1$-$ДУ_2$) connected to the primary circuit of the power transformer. The electronic block automatically maintains the protective potential.

Leads from the reference electrode (plus) and from structure (minus) are connected to the electronic block input (to terminals marked "signal").

The signal is received by the amplifier, the first stages of which are transistors T_{17} and T_{16} of type П 106 and П 103, respectively, in a Darlington circuit with a high input (50 kohm) and low (5-7 ohm) output impedance. The stage with transistor T_{15} is in a common base configuration and has low input impedance and insignificant DC drift.

The operating point of the amplifier is established by variable resistor R_{50}. By adjusting R_{50} the base bias of transistor T_{15} can be set to the necessary amplifier DC conditions. Further amplification takes place at transistor T_{14}. The output stage, T_{13}, is an emitter follower. The amplification factor of the amplifier is 150. The DC drift is 3.3 mV/degree.

The УПТ supply of the pulse device has two identical transistor sources of stabilized voltage. Transistors T_2 and T_{11} are installed on heat sinks with a power dissipation not less than 5 W each.

The bridge D_1 - D_4 supplies the reference voltage source during set-up of the amplifier operating point. The bridge D_{11} - D_{14} supplies the base circuit of transistor T_4 with positive sinusoidal pulses.

Thyristor Controlling Device. Rectified sinusoidal pulses of 100 Hz are received by the base of transistor T_4 (type МП-42) from the D_{11} - D_{14} bridge. The pulses applied to T_4 are positive in polarity and shuts off the transistor for the duration of the pulse. During T_4 shut-off, capacitor C_4 is charged through the resistor R_{15}. When the amplitude of the pulse decreases to zero. T_4 conducts and C_4 is instantaneously discharged. In this manner, saw-tooth pulses of 100 Hz are formed at the collector of T_4. The slope of the saw-tooth pulses is determined by the time constant of R_{15} and C_4.

When the voltage on C_4 reaches the threshold of transistors T_5 and T_6, type МП-42, the circuit triggers and a negative pulse is formed across resistor R_{18}. The duration of this pulse could last from zero to T/2, where T is the period of 100 Hz pulses. The duration of this pulse depends on the control voltage on resistor R_{24}. The controlling current passes from the output stage of the amplifier through series resistors R_{32} - R_{36}. This resistor chain makes it possible to control the conduction angle of the thyristors regardless of the signal value at the amplifier input.

Approximate control is achieved by resistors R_{32} - R_{35}, and fine control by resistor R_{36}.

Transistors T_7 and T_8 form an emitter coupled multivibrator which generates rectangular 2.5 kHz pulses, with a rise time of 1-1.5 μsec and a duty cycle of 4-5. The required time for the multivibrator to produce pulses depends on the pulse duration at the collector of T_8, and can vary from zero to T/2. These sharp-edged pulses with negative polarity flow from the

collector of T_8 through C_6 - R_{29} to the base of transistor T_9. A transformer functions as the load for T_9, and pulses from its windings reach the control electrodes of the thyristors.

Diodes D_{16}, D_{17} and D_{18} clamp the positive voltage spikes at the collector of T_9 and at the control electrodes of the thyristors. Stabistors are used at D_{17} and D_{18} to limit the amplitude of the control pulses to 9-10 V. Taps at the secondary windings of the output transformer permits use of different types of thyristors.

The transformer characteristics are: core Ш 20 x 20, primary winding B = 300 turns, diameter 0.3; secondary windings B = 400 + 300 turns, diameter 0.3.

Changes in the input signal value increases or decreases both the current and voltage at the voltage booster output (power rectifier). In this way the protective potential is maintained on a structure as a function of the received signal.

The DUT unit can function either with automatic or manual control.

A switch on the instrument panel changes the operation conditions of the DUT-AKKh unit. In the case of manual control, the electronic block is turned off and the unit functions as a powered nonautomatic draining device.

The draining current and voltage at the power rectifier output are measured in this case with an ammeter and voltmeter located on the front panel.

A special filter circuit is used for elimination of radio frequency interference.

The unit is turned on by a rotary switch located on the front panel and by a toggle switch for the electronic block.

The base or a support rack for the installation of DUT-AKKh unit should be elevated by 0.4-0.5 m over the ground surface.

The draining circuit is prepared by connecting the positive pole of the power rectifier (screw marked with + on the terminal board) to a cable attached to a rail. The negative pole of the power rectifier is connected to a cable attached to the underground structure. Twin shielded cable is connected to the terminals marked "signal"; one wire from the minus terminal is connected to the protected underground structure, and the other is connected to the reference electrode.

The reference electrode is a stationary nonpolarized copper sulfate electrode or a steel tube 20-35 mm in diameter. This tube should be inserted into ground not less than 20-30 cm below the freezing level.

Power is supplied to DUT-AKKh unit by a cable of not less than a 500 V breakdown rating and a cross-section not less than 6 mm^2 (220 V, 50 Hz).

Prior to testing of the draining unit, jumpers at the terminal block of the secondary winding of transformer TP_3 should be installed according to the projected protection voltage (6 or 12 V). All units are produced in the 6 V configuration. Jumpers are used if it is necessary to operate at 12 V. Before turning the unit on the switch is turned to the "manual control" position, the thyristor conduction angle control (switch Π_1 and variable resistor R_{36}) to intermediate positions, and the reference voltage controlling device (variable resistor R_4) to the position 1 V. Thereafter the rotary switch and the toggle switch TB_1 for the electronic block are turned on. The presence of supply voltage at the unit input is indicated by light ЛО after the toggle switch is turned on. The presence of voltage in the electronic block is tested by a push button (a light should appear on the front panel). After establishing the presence of the supply voltage, the regulator of the reference voltage R_4 is turned right (or left) until all control instruments (DC voltmeter and ammeter A) show the presence of current and voltage in the draining circuit. Values of voltage and current should gradually change during the adjustment of the variable resistor R_{36}. If insufficient current is delivered, the switch Π_1 is turned into the next position (the knob of resistor R_{36} should be moved counter clockwise first) and the required current in the circuit is adjusted by the variable resistor R_{36}.

After checking the unit operating under manual control, it is tested for automatic control. First the reference electrode and underground structure are disconnected from the control block input. Then a DC voltage of 0-1.5 V is supplied (observing the polarity marked on "signal" terminals). A voltage divider (a potentiometer with resistance of 0.1-1 kohm) and a galvanic cell of type 332 (FBS-0.25), connected as shown in Figure 34, can be used for this purpose. After reaching the required voltage with the use of potentiometer R_1 at the input block (points 88-89 in Figure 33), the reference voltage is adjusted (resistor R_4) until the volt and ammeter show the presence of current and voltage at the unit output. The current will vary up and down during

adjustment of the DC voltage by the potentiometer. At the same time it should be established if the draining unit output current changes over a certain range when switch Π_1 is turned into a new position and the resistor R_{36} knob is moved when the signal voltage is varied over ± 30 mV.

At the same time the accuracy in the adjustment of control circuit is checked. When the adjustment is correct, the current at the unit input will increase with decreasing signal voltage and it will reach its maximum value when the control circuit is disconnected.

(a) stabilized rectifier

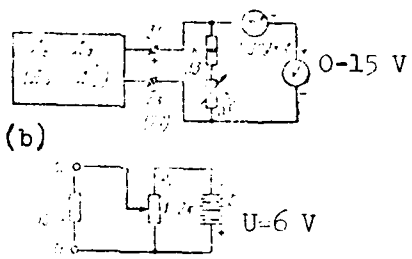


Figure 34. Connection diagram of auxiliary circuits used for adjusting the powered draining unit type DUT-AKKh.

After finding the automatic control circuit functional, leads from the reference electrode and protected structure are connected to terminals 88 and 89. At this time the automatic control circuit is checked in the presence of an actual input signal. If the protective potential on the structure is insufficient and the unit output voltage low, the switch Π_1 is turned into another position and the unit output current is gradually increased (by adjusting resistors R_{36} and R_4) until the potential on the structure reaches the required value with respect to the reference electrode.

It should be kept in mind that the same adjustment sequence must be followed for the input circuit of the control block if the need arises during automation operation of the unit. Special attention should be paid to the reference voltage supplied from R_4 and stabilized rectifier D_1 - D_4 to the signal circuit. The fifth position of the switch Π_1 combined with the minimum resistance of R_{36} (limiting positions of the resistor knob) provide the optimal operating conditions of the draining unit.

In the case of a break-down in any of the unit subassemblies, the thyristor control device, stabilized rectifiers and the transistor amplifier should be checked first for correct voltages on the transistor electrodes of the DUT-AKKh control circuits (Table 11). If the malfunction can not be easily detected, a complete check of all subassemblies of the control block should be conducted. First, check all rectifiers, followed by the pulse and amplifier circuits.

In order to adjust and test the stabilized rectifier which is used as the reference voltage source, the switch is turned into the position marked "manual". At this time the stabistor D_5 voltage should be 7.5 - 8 V, and should change when the resistor R_4 is adjusted to change the feed voltage within +10 to -30%. When the resistor R_4 knob is moved from one limiting position to another, the voltage between the moving and common lead should change between -0.5 to -5 V without any fluctuations. Instruments of type M-231 or volt-ohmmeters of any type can be used for these measurements.

Effective variable voltage on the transistor electrodes (V)

Transistor	Base	Collector	Emitter	Remarks
T_4	1.9	4 1	-	
T_5	4.1	0.38	6.7	
T_6	0.12	1.9	6.7	The pulse voltage on the collector of T_9 is 13 V when DV_1 and DV_2 are 100% conducting
T_7	0.73	3.7	1	
T_8	1.7	1.35	1.35	
T_9	1.1	8.2	-	

Adjustment of the remaining stabilized rectifiers is confined basically to finding the optimum resistance value of R_8 and R_{37} in order to obtain minimum ripple of the output voltage. A proper selection of resistors R_6 and R_{39} establishes the control range of the rectifier output voltage.

Rectifiers can be checked with an auxiliary circuit shown in Figure 34a. The output voltage of 15 V can be established with the resistor R_{11} (or R_{42}, Figure 33) and the current of 0.3 A is adjusted with the resistor R_2. These parameters should be stable. Heating of the rectifiers under load for 10-15 minutes is a required procedure. The above voltage and current

Table 11. Transistor electrode voltage of the control block of DUT-AKKh

Transistor	Without input signal			With input signal			Remarks
	Base	Collector	Emitter	Base	Collector	Emitter	
T_1	-35	-15	-35				
T_2	-15	-35	-15				
T_3	-9	-15	-9	First stabilized rectifier with the voltage adjustment within 12 - 27 V.			
T_4	+4	-1.5	0	+4	-7	0	
T_5	-1.5	-12.6	-4	-7	-7.7	-6.6	
T_6	-4.2	-13.5	-4	-2.4	-16	-6.6	
T_7	-7	-11.5	-6.7	-5.8	-11	-5.9	
T_8	-[illegible].1	-6.8	-6.7	-6.1	-8	-5.9	
T_9	+0.13	-17	0	-0.03	-13	0	
T_{10}	-35	-15	-35	Second stabilized rectifier with the voltage adjustment within 12 - 27 V.			
T_{13}	--	--	--	-6.1	-15	-5.4	Voltage on transistor electrodes of VПТ was measured with input signal which provides 50% conduction of Dy_1 and Dy_2 thyristors.
T_{14}	--	--	--	-0.65	-0.03	-0.65	
T_{15}	--	--	--	-3	-0.65	-3.7	
T_{16}	--	--	--	-3.1	0	-3.7	
T_{17}	--	--	--	-3.7	-15	-3.1	

NOTE. Cathode voltmeter type BK7-3 was used for voltage measurements. Measurements were carried out with respect to the terminal marked "common + feed".

values should be constant when the supply voltage changes from +10 to -30% (this can be checked with LATR-1 or LATR-2). In order to adjust the pulse device, a lead connecting terminal 50 (Figure 33) of the impulse block (diode D_{15} - resistor R_{24}) with switch Π_1 should be temporarily disconnected. Then a source of DC (the voltage of which can be changed from 0-6 V) is connected in series to resistor R_{24} (as is shown in Figure 34b).

After this preliminary procedure, the pulse block is checked stage by stage. The vertical input (Y) of an oscilloscope (of type C1-1, for example) is connected first to terminals 31-49 with the transistor T_4 base serving as the common positive pole (Figure 33.) The shape of voltage should correspond to that shown in Figure 35a when the circuit operates normally (the pulsed rectified voltage recorded from bridge D_{11} - D_{14} with a frequency of 100 Hz). When two half-waves of positive pulses are supplied to the transistor T_4 base, saw-tooth pulses with a fast return are obtained at its output across capacitor C_4. The transistor T_4 is cut off by positive pulses and conducts by current flowing through resistor R_{14}. Duration of the saw-tooth pulses in the collector circuit transistor T_4 and in the transistor T_5 base depends on the control voltage supplied to terminals 31 and 50 (Figure 33). When this voltage is changed between 3 - 6 V, these pulses change from 1 to 0 (i.e., from T/2 to 0 where T = 0.02 sec).

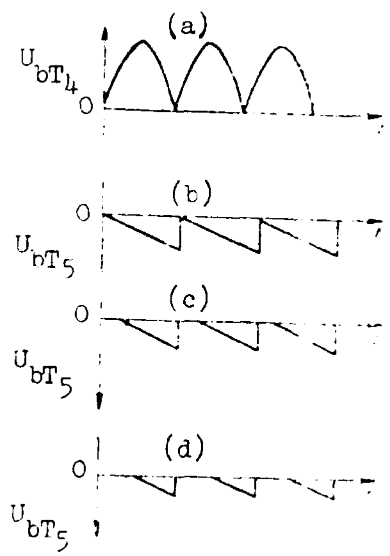


Figure 35. Shaping the saw-tooth pulses and controlling their duration.

Figures 35b, 35c, and 35d show the saw-tooth voltage at V_c = 3; 4.5; and 5.5 V, respectively.

The shape of the saw-tooth pulses can be adjusted by proper selection of the resistance of R_{14} and R_{15} (basically of R_{14}).

The next step requires connection of the oscilloscope to terminal 53 (Figure 33, collector of the transistor T_5) where rectangular pulses are formed. Their duration depends on the duration of the saw-tooth pulses received at the base of T_5. When the control voltage is changed between 3-5.5 V (Figure 36), the width of these pulses also changes.

After connecting the oscilloscope input to 57 (Figure 33), which is collector of transistor T_6, it is necessary to determine if the shape of the impulse is the inverse of the voltage on the collector of T_5. The pulse flows from the collector of T_6 through R_{19} - C_5 to the second trigger circuit with transistors T_7-T_8. The parameters of this circuit are selected such as to make the voltage on the collector of T_6 reach a maximum value (12.6 V) and trigger the circuit to produce rectangular pulses at a frequency of 2.5-3 kHz. When the voltage at the collector of T_6 decreases to 7.5-7.7 V, T_7-T_8 stops producing pulses. Thus, the duration of the burst of pulses corresponds to the duration of the rectangular pulse at the collector of T_6.

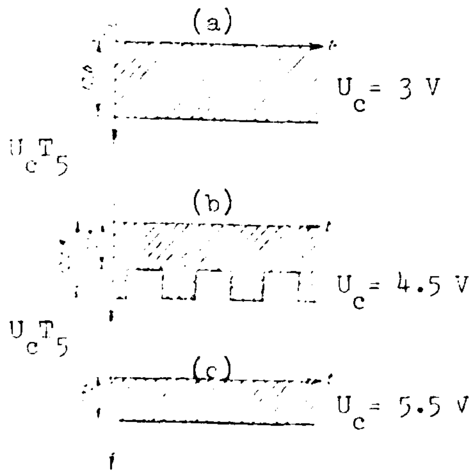


Figure 36. Value and shape of the voltage at the collector T_5 as a function of control voltage.

Figure 37 shows the voltage shape at point 57 (Figure 33), the collector of T_7. An identical picture is observed when the oscilloscope is connected to terminal 65 (collector of T_8) but the pulses in this case have a negative polarity.

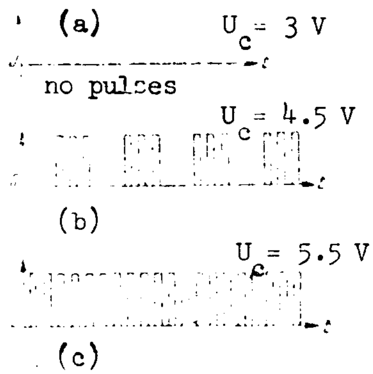


Figure 37. Voltage at the collector of T_7 as a function of the control signal.

During the adjustment of the pulse circuit the parameters of T_7-T_8 trigger are established by the proper selection of the resistance of R_{27} and R_{28}. The control pulses flow to the transformer coupled power amplifier from the collector of T_8 through C_6-R_{29}. The power amplifier is designed with transistor type П214 (T_9) which operates under switching conditions.

A burst of pulses flows to the control electrodes of thyristors DY_1 and DY_2 from windings II and III of the output transformer TP_2.

Phasing of the output windings of TP_2 is accomplished with an oscilloscope, the vertical input (Y) of which is connected in sequence to ends of the secondary windings II and III (first disconnecting them from the control electrodes of the thyristors). Diodes D_{17} and D_{18} should be disconnected during adjustment. After recording the polarity of the voltage at the secondary windings output, they are connected into the circuit in such a way that pulses with positive polarity are received by the control electrodes of thyristors DY_1 and DY_2. Without disconnecting the oscilloscope, diodes D_{17} - D_{18} are reconnected (the amplitude of the pulse should not decrease during this procedure). If the diodes are erroneously connected, the amplitude of the pulses will decrease sharply.

The device is fed by 15 V from the stabilized rectifier.

The control pulse circuit is checked next. When its input voltage changes from 3 to 5.5 V at terminal 53 (Figure 33), a voltage drop from 12.6 to 7.6 V should take place. Two MJIT2 150 ohm resistors are used as a load for the output transformer. With this load the amplitude of the pulse is 7.5-8V. Oscilloscope C1-1, C1-5 or any other can be used for these measurements

Voltage changes from -3 to 5.5 V at the control device input changes the duration of the burst of pulses from 0 to 1. When the conductor connecting the amplifier input (base of T_{17}) and the signal source at the control device output is disconnected, the duration of the burst of pulses is 1.

The first two stages of the amplifier, with transistors T_{17} and T_{16}, do not need any adjustment. The reference voltage at the amplifier output should be 3.8-3.85 V during adjustment procedures.

Voltages at points shown in Figure 33

87	3.7 V
86	3.1 V
84	3.7 V
85	3 V
83	0.65V
81	0.05V
80	6.1 V
50	5.4 V

Deviations could amount to ±20%. Cathode voltmeter BK7-3 can be used for measurements with respect to the common terminal.

Adjustment of the amplifier is confined basically to selection of resistors R_{45} and R_{30} in the T_{15} and T_{14} stage. The amplifier is adjusted in the following sequence. The operation switch is turned to the position marked "manual", a lead between terminals 50 - 50A is temporarily removed, and capacitor C_{11} and the base of T_{17} are disconnected. A voltage of 20-50 mV at 400-1000 Hz is supplied to the amplifier input from the tone generator (Г3-33, for example) by a shielded cable through a 0.01-0.1 kf capacitor. An oscilloscope is connected at the amplifier output.

The tone generator voltage and oscilloscope input sensitivity are adjusted to preserve the sinusoid shape and to make its dimensions easy for

observation. By changing the resistance of R_4, the operating point is adjusted so as not to limit the sine wave on either the positive or negative peaks. This adjustment is done with resistor R_{50}. The amplifier voltage is gradually increased while the resistance of R_{50} is adjusted. In this way symmetrical clipping of the sine wave is achieved.

It should be kept in mind that by changing the supply voltage with R_{42} (control of the rectifier output voltage) the necessary conditions for the amplifier can be established. The allowable supply voltage for the pulse circuit is 14-16 V. The amplification factor of УПТ is K_{max} = 140-150.

After testing the transistorized amplifier, the switch is turned to the "manual" position and the resistor is adjusted until the voltage of 3.7-3.8 V is achieved at the amplifier input. At the same time a voltage of 5.4 V should be at the amplifier output (point 50).

When the input voltage is changed by $\pm$25 mV with respect to the required voltage, the output voltage changes from -3 to -5.5 V. When the input voltage changes from 0 to -5 V, the output voltage changes from -12 to 0 V.

3. PRELIMINARY TESTING OF ELECTRODRAINING UNIT AFTER MAJOR OVERHAUL OR LONG STORAGE

Prior to a full scale operation all subassemblies of every unit should be checked. First the insulation resistance of the current-conducting elements from the unit frame. These measurements can be done with megohm meter at 500 V. The insulation resistance should be not less than 10 kohm per 1 V of operating voltage.

The resistance of the signal circuits is checked with an electron-tube ohmmeter (for example, the universal voltmeter BK7-3). The insulation resistance of input leads should not be less than 1 Mohm.

The power amplifier is checked by first disconnecting the thyristor block Dy_1 and Dy_2 and supplying the primary winding of the power transformer TP_3 with AC of 220 V, 50 Hz. Jumpers on the terminal block of the secondary winding of TP_3 should be installed in the position marked "6 V" and the load resistance of 0.05 ohm (calculated for operating current up to 400 A) should be connected at the rectifier output. This will produce the rectifier output voltage of 6 V and the current will reach 300 A in the load circuit. Under

these conditions the power rectifier must be tested for 20-30 min while the temperature of the TP_3 windings and of rectifiers DC_1 - DC_6 (BK-200) should be recorded. This temperature should not exceed 70°C when the temperature of surrounding air is 20°C.

Next, jumpers in the secondary winding of TP_3 are set up in the position marked "12 V" and a load resistance of 0.1 ohm is connected at the rectifier output. The voltage at the rectifier output is then measured. When the output voltage reaches 12 V, the current in the load resistance should be of order 120 A.

The next step requ... ·s a test run of the unit under conditions of manual control. After turning the switch (toggle switch) into "manual control" position, set switch Π_1 and variable resistor R_{36} in the central position and R_4 into the position marked "1 V". Turn on the rotary switch and the toggle switch of the electronic block TB_1.

If current is present in all subassemblies of the unit (as indicated by the light), the regulator of the reference voltage, R_4, is turned slowly right (or left) until the measuring instruments show the presence of current in the load. Draining units can be tested by manual control in position 6 or 12 with output resistance indicated above. The current value in the load resistance should vary when variable resistor R_{36} is changed regardless of the position of switch Π_1 . The current maximum in the load is secured by the fifth (the last position at right) position of this switch.

Automatic testing is accomplished by turning the toggle switch TB_2 to the position marked "automatic control" and DC of 0-1.5 V is supplied to the input terminals marked "signal" The DC voltage is measured by a DC voltmeter of type M-231, for example. After adjusting the signal voltage to 1 V at the unit input, the reference voltage is adjusted with the resistor R_4 until recording instruments show the presence of current in the load resistance. This current should reach a maximum and minimum value when the input voltage is varied between $\pm$20 - 30 mV. The accuracy in the adjustment of the control circuit is checked at the same time. The current at the unit output in this case will increase with decreasing voltage (with respect to the set-up of the reference voltage) and reach maximum value when the signal chain limits.

4. AUTOMATIC CATHODE STATION TYPE AKS-AKKh

The cathode station of type AKS-AKKh is designed as a dismountable cabinet with individual subassemblies fixed to frame. The cabinet has a front door which can be locked. The external shape and size of this unit is identical to that of the UD-AKKh and DUT-AKKh units (cabinet is standardized).

The cathode station can be installed on a base 0.4-0.5 m above the ground surface. (See Figure 28.)

The assembly of AKS-AKKh differs very little from that of other draining units. The negative terminal of the power amplifier is connected by a copper cable 25-35 mm^2 in size to the ground anode. During installation of the ground anode, all measures should be taken to insure stable resistance of the grounding. It should be kept in mind that with increasing resistance of the ground anode the maximum potential value (which can be achieved by a given unit) decreases.

The negative terminal of the power rectifier is connected by a cable to the underground structure. The signal line is made of a twin insulated cable 1.5-2.5 mm^2 in size. The terminal marked "minus" is connected to the protected structure, and the "plus" terminal to the reference electrode. The latter is made of a steel pipe 20-35 mm in diameter which is inserted in ground 20-30 cm below the ground freezing zone and not far from the protected structure.

The current to the unit is supplied with any twin cable which can withstand 500 V and is 6-10 mm^2 in cross-section.

The AKS-AKKh unit consists of individual circuit modules. The power transformer is located at the frame bottom and is attached to rails. The terminal block of the secondary windings B_2 and B_3 has studs with jumpers which are used for connecting the windings for a given output voltage and current. The DC board and input board are located at the left- and right-hand side of the transformer, respectively. Blocks of power diodes and thyristors are located in the frame center; between these blocks there are the DC ammeter and voltmeter (measuring instruments of the protection circuit).

The subassemblies of the control circuit (transistorized amplifier and a phase-shifting device) are located in the upper corners of the frame. These subassemblies can be easily moved along the support rails and are dismounted for checking and adjustment.

Figure 38 shows the principal schematic diagram of the AKS-AKKh unit.

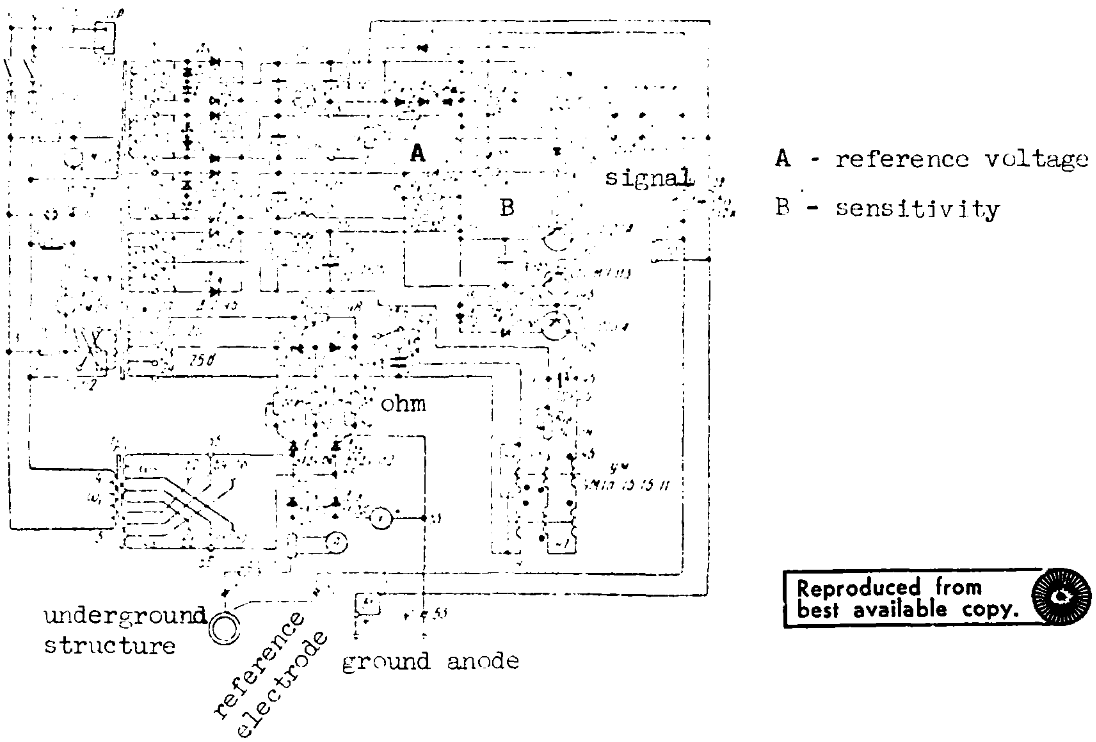
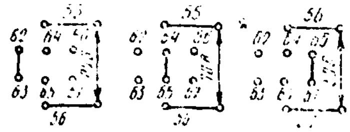


Figure 38. Basic schematic diagram of the cathode station AKS-AKKh.

Depending on the position of the jumpers on the terminal block of the secondary windings of the power transformer, the sections B_2 and B_3 can be connected either in series or parallel with respect to each other. In addition, each of these sections has two leads from taps on the turns. When windings B_2 and B_3 are connected in parallel, the maximum output current could reach 70 A; and when they are connected in series, the maximum current could reach only 35 A. Depending on different switching variations of these windings (Figure 39), the maximum output voltage of the station could vary between 25-100 V.

The design of the AKS-AKKh station allows a continuous adjustment of output voltage for automatic and manual control. Switching from one to the other type of control (Figure 38) commutates the reactive elements of the

series connection of the TP-3
transformer windings (up to 35 A)



parallel connection of the TP-3
transformer windings (up to 70 V)

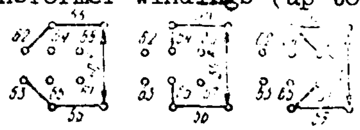


Figure 39. Connection diagram of the secondary transformer windings of the cathode station AKS-AKKh.

phase-shifting device (capacitor C_{11} and secondary windings of УМ) which controls the conduction angle of thyristors D_{25} and D_{26}.

When the unit is switched to automatic control, two AC windings of the magnetic amplifier УМ (which are connected in series) are connected to the phase bridge. By adjusting the current value flowing in the УМ winding it is possible to change the inductance of the AC windings over a large range. УМ winding is the controlling element in the phase-shifting device. Therefore, the necessary phase shift between voltages at the phase bridge input and output is secured at this position of the selector by changing the current flowing in windings of the УМ. When the current value reaches I_{max}, the magnetic circuit of УМ becomes saturated and the phase shift between input and output voltages of the control bridge approaches to zero. If no current is present in the УМ windings, the phase shift between the anode and the controlling voltage applied to thyristors D_{25} - D_{26} reaches its maximum value (almost 180°) and the output voltage of the power amplifier becomes minimal.

The small power transformer TP_2 also supplies current to the control circuits of thyristors D_{25} - D_{26}. Variable resistors R_{15} and R_{17}, as well as the resistor R_{16}, which is connected in the common cathode circuit of the thyristors, control the current in the control circuit. These resistors are connected in series with the control electrodes of the thyristors. Silicon

diodes type D226 (D_{23} and D_{24}) are needed to clamp the reverse voltage on the control electrodes of the thyristors.

The resistance of variable resistors R_{15}, R_{16} and R_{17} is adjusted only at the manufacturing plant during a general adjustment of the complete unit (when the control current of both thyristors is adjusted), or when damaged thyristors must be replaced.

The control windings of УМ are connected in series and are attached to the output stage of the DC transistorized amplifier УПТ. The latter is used for the magnetization current adjustment in the control windings of УМ. The signal from the protected structure and from the reference electrode is supplied to the УПТ input.

The AKS-AKKh unit is equipped with a three-stage amplifier, УПТ, with transistors T_1, T_2 and T_3 DC coupled in a common emitter configuration. Because УПТ must remain operational during excessive temperature variations (-40 to +35°C), measures were undertaken to make its stages and current supply thermally stable.

P-np and n-p-n transistors type П 27A and МП 113 with small leakage currents are used in the first stages of УПТ. The reverse current of the collector junctions ($I_{c\ rev}$) of П 27A transistors does not exceed 0.8 μA and of МП transistors does not exceed 0.5 μA at 40°C. The first two input stages of the amplifier can be thermally stabilized by the proper selection of transistors having equal but opposite leakage currents. When the magnitude of the leakage currents increases simultaneously (for example, in the case of a temperature increase) the parameters of the УПТ stages will remain unchanged. (The reverse currents of collector junctions of T_1 and T_2 transistors compensate each other). The thermal stabilization of the output stage of УПТ (T_3) is achieved by connecting two silicon diodes of type D244B (D_{21} and D_{22}) in the emitter circuit of the transistor П 216A. When these diodes are connected in the forward direction, they produce thermal stabilization of the emitter circuit of transistor T_3.

The first two stages of УПТ receive the current from the stabilized rectifier designed with a bridge consisting of four diodes of type D226 (D_2-D_{12}). This rectifier is equipped with a parametric voltage stabilizer containing one silicon stabistor D808 (D_{19}) and two resistors R_8 and R_9 (stabilizing and load, respectively) The value of the stabilized DC voltage

at resistor R_9 is 7-8 V (depending on the parameters of the stabistor D_{19}). The rectifier also has a LC filter with choke ДР$_1$ and electrolytic capacitors C_5 and C_7. The positive rectified voltage is connected to the emitter of T_1 and to the collector of T_2 (through R_{11}). The negative supply voltage is connected to the emitter of T_2 and to the collector of T_1 through the emitter-base of T_2.

A full-wave rectifier with two silicon diodes type D242B (D_{12} and D_{14}) feeds the output stage of the УПТ. At the rectifier output there is an LC П filter (choke ДР$_2$ and electrolytic capacitors C_6 and C_7).

The negative lead (the mid-point of the secondary winding of the power transformed TP$_1$)is connected to one end of the УМ control winding (four control windings of УМ are connected in series) through a semi-variable wire resistor of type ПЭВР -15 (R_{18}). The positive leads of D_{13} and D_{14} are connected to the positive terminals of D_9-D_{12}, and to the emitter of T_3 through the stabilizing diodes D_{21} and D_{22}. The other end of the control winding of УМ is connected to the collector of T_3 (type П 21-216A).

The control signal from the reference electrode and the structure is received at terminals marked "signal" and passes to potentiometers through R_{12} and R_{13}. These potentiometers control the reference voltage of R_4 and reference voltage of R_7.

A second supplementary source of emf is added to the signal circuit of AKS unit, in contrast to similar protection units equipped with only the usual source of reference voltage, which provides the reverse characteristic of the control device (i.e., increase of current with decreasing signal voltage). This additional source of emf is necessary for setting up the operating point of transistors T_1 and T_2 and for starting the control circuit of the AKS-AKKh unit. This source is a conventional nonstabilized rectifier receiving the current from one of the secondary windings of the power transformer. The rectifier is designed with a bridge consisting of four silicon diodes type D226 (D_5-D_8). Capacitor C_4 and voltage divider R_7, which is used to control the output voltage of the secondary source within 0-5 V, are attached to the rectifier output. The polarity of this voltage to the signal circuit is such that when the voltage at potentiometer R_7 decreases (for example, a voltage drop in the AC line) the output current of УПТ increases. In this way the second supplementary source of emf, which is connected in

series with the signal voltage received from the protected structure and from the reference electrode, functions to compensate for the instability of the unit supply line.

A stabilized rectifier with a bridge containing four silicon diodes D226 (D_1-D_4) is the source of reference voltage for the signal circuit of the AKS-AKKh unit. A П section RC filter consisting of two electrolytic capacitors C_1 and C_3 and resistor R_1 are connected at the rectifier output. The parametric voltage stabistor of this rectifier has two stages containing four silicon stabistors D_{15}-D_{18}. Diodes D_{15} and D_{18} are used as semiconductor voltage stabistors, and diodes D_{16} and D_{17} (connected in the forward direction in series with D_{18}) serve as thermocompensators for the reference voltage source. Because diodes D_{15} and D_{18} (D808), which are connected in series with the stabilizing resistors R_2 and R_3 and to the negative terminal of the rectifier D_1-D_4, possess different stabilization voltages (8 and 11 V), a difference voltage of 3 V appears in the load resistor R_4 (the design provides a lower stabilized voltage than the minimum stabilization voltage of silicon stabistors D808).

When a negative signal voltage is received at the base of transistor П27A from R_5 (marked "sensitivity") which exceeds the positive voltage supplied to П27A by diode D_{20}, the transistor conducts and the collector current increases. As a result transistor МП 113 conducts less and its collector circuit drops from 10-12 to 6-7 mA which in turn causes a voltage change in resistor R_{11} (connected to the base of transistor П 216A) from 1.8-1.6 to 1.2-1.3 V. Transistor T_3 then conducts more and the current in its collector circuit increases from 10-12 to 50-300 mA (depending on the value of the error signal and reference voltage at the УПТ input). This in turn changes the current value passing through the control windings of УМ and also determines the conduction angle of transistors D_{25}-D_{26}, and consequently the unit output voltage.

5. TURNING ON AND ADJUSTMENT OF THE CATHODE STATION TYPE AKS-AKKh

Before trial runs of the AKS station it is necessary to attach jumpers to the secondary winding of the power transformer to set the output voltage between 25-100 V.

At 25-50 V, both sections of the secondary winding (Figure 39) are connected in parallel. (At 25 V jumpers are installed between points 55-66 and 56-67; 35-55-64; 56-65; and at 50 V, between 55-62 and 56-63). The current in the protection circuit could reach 70 A. If it is necessary to obtain 100 V at th. AKS unit output, both sections of the secondary winding of TP_3 are connected in series. When the operating voltage is 70 V, jumpers are installed between points 64-65; and when it is 100 V the jumpers are attached between 62-65. The maximum current in the protection circuit should not exceed 35 A in this case. Figure 40 shows the switching order of the windings.

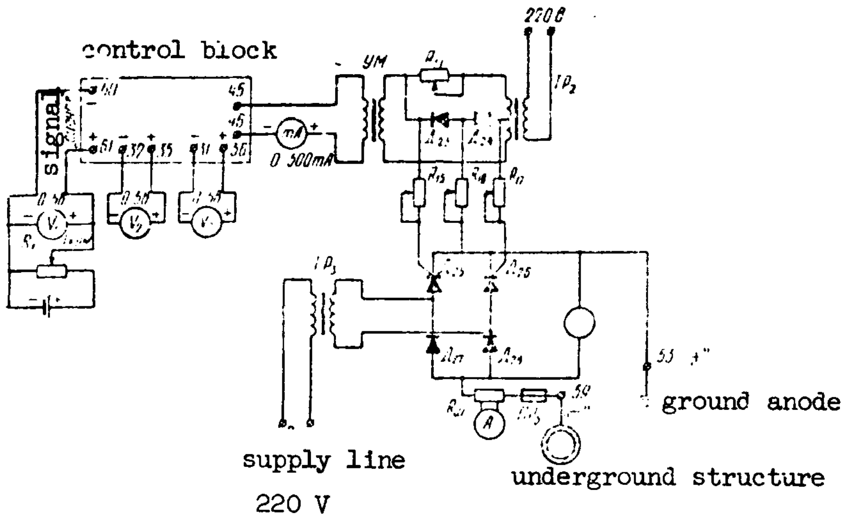


Figure 40. Schematic diagram for connecting measuring instruments during checking and adjustment of the cathode station type AKS-AKKh.

Before the trial run of the AKS unit the switch $П_1$ is turned to the position marked "manual" and the slide of the variable resistor R_{14} is moved to a central position (marked "phase"). The unit then is turned on with the rotary switch ПК and presence of current in primary windings of power transformers is indicated by lights ЛО and ЛС-2.

Before attempting to set up the automatic operating conditions of the AKS unit, it should be operated under manual control. If the output terminal 59 (negative) and the terminal 53 (positive) are connected correctly to a structure and an anode grounding, respectively, and there is AC voltage

at the power transformer outputs, the slide of the variable resistor R_{14} is moved slowly in one direction and then in the other. The measuring instruments should be observed at the same time. If the readings of the voltmeter and ammeter, which are connected at the power transformed output, remain unchanged during rotation of the knob of the variable resistor R_{14} clock-wise and counterclock-wise, the knob is placed in the central position and toggle switch $ТП_1$ (phase) is turned to the outmost position. Then the previous operation is repeated until voltage appears at the AKS unit output. The operator should be able to change this voltage continuously from maximum to minimum with the resistor R_{14} (phase).

If the power amplifier circuit and the phase rotating device of the AKS unit function properly, the automatic voltage regulator is adjusted next. First, the reference electrode and the protected structure are temporarily disconnected from the automatic control circuit (terminals 61 and 60). Then a DC voltage which can be controlled between 0-3 V is supplied to the terminals marked "signal" observing their polarity. Two galvanic cells of type 332 (FBS-0.25) connected in series can be used for this purpose, or other suitable DC sources.

After connecting a suitable potentiometer (such as variable resistor of type СП-1 with a resistance of 470 ohm to 0.5 kohm) in parallel with the galvanic cells, the voltage from the potentiometer slide and from one end of resistor is supplied to terminals 60 and 61. The negative source of emf should be connected to terminal 60 and the positive to terminal 61.

Then the knob of the variable resistor R_{14} (phase) is turned to a central position and toggle switch ТП1-2 (phase) is turned to outmost position. Sources of the supplementary voltage at the УПТ input are checked next. After attaching a DC voltmeter (0-5 V scale) to terminals 32-36 (reference voltage) and 32-35 (comparison voltage), the rotary switch is turned on. The indicating light verifies the voltage presence at the transformer output. During the next step, variable resistors R_4 (reference voltage) are rotated in turn and the presence of voltages at terminals 32-35, and 31-36 and the extent of their range is determined. The adjustment is made with resistors R_4 and R_7, and the range should be between 0-4 and 0-5, respectively.

The comparison voltage in the signal circuit is adjusted with resistor R_7 between 0.2-0.5 V, and the signal voltage at terminals 60-61 within 1 V. A voltmeter attached to terminals 32-35 and 60-61 is used during this procedure. Then the variable resistor R_6 (sensitivity) is turned to the position of maximum resistance (10 kohm) and R_{12} (signal) to the position of minimum resistance. By gradually changing the reference voltage with resistor R_4, the appearance of current in the protection circuit is achieved.

A more detailed checking of the УПТ can be done by connecting a DC ammeter (0-0.5-1 A scale) in series with the control windings of УМ. This can be accomplished by disconnecting one of the ends of the control winding from terminals 45 or 46 and connecting it to the ammeter. The increase of the output voltage of УПТ as a function of the difference between the signal and reference voltage is determined from the ammeter readings. Figure 40 shows the connecting diagram of measurement instruments during adjustment of the AKS-AKKh unit.

If current is present in the output circuit of УПТ and in the control windings of УМ, its value is set between 70-100 mA by the variable resistor R_4, or by changing the signal voltage at terminals 60-61. A presence of current in the protection circuit is established with the resistor R_{14}. The maximum current at the УПТ output is set up by a gradual increase in the difference between the signal and reference voltages. Upon reaching the maximum current at the УПТ output, the voltage at the output should stop increasing. If this is not the case, an adjustment can be made with the trimming resistor R_{18}. It should be kept in mind that the maximum voltage at the station output is determined by the position of the jumpers at the terminal block of TP_1 secondary windings and also by the position of the adjusting knob of the variable resistor R_{14} which controls the conduction angle of the thyristors D_{25} and D_{26}.

The automatic control circuit should operate over the entire range of different signal voltages which could be encountered during operation of the AKS-AKKh station.

Upon completion of testing the unit with an experimental signal, the auxiliary source of emf is disconnected from terminals marked "signal" and leads from the reference electrode and protected structure are connected to terminals 60 and 61. During the next step the cathode station is run

under the actual signal, and all necessary adjustments are done. The normal operating condition of the AKS-AKKh station should be controlled by just one variable resistor, R_4; and the maximum output voltage set by resistor R_{14} (within each range of output voltages established by switching the secondary windings of TP_1).

6. PULSE CATHODE STATION TYPE IKS-AKKh

The automatic pulse cathode station IKS-AKKh externally resembles the UD-AKKh units. Recommendations on installation and mounting of the cathode station AKS-AKKh apply to the IKS-AKKh station.

The IKS-AKKh station consists of individual modules. The power transformer TP_1 is located in the lower right-hand corner of the frame, with the AC terminal board with fuses ΠP_1, ΠP_2, ΠP_3, plug connector ШР and rotary switch ПВ located at the left side. The electronic control module is mounted in a special opening having a door. The module is located at the left side approximately in the frame center. Opposite at the right-hand side are thyristors DY_1 and DY_2 with finned heat sinks mounted in a rectangular ventilation duct. This duct is a tube (both ends of which are open) with free air circulation because of convection. Measurement instruments of the protection circuit (DC voltmeter and ammeter) and an illuminating light are located in the lower part of the cabinet. Figure 41 shows the principal schematic diagram of the IKS-AKKh station.

The power rectifier is designed with a single phase full-wave circuit with a center tap and two type ВКДУ-150 thyristors ($ДУ_1$ and $ДУ_2$ which are connected to winding II of TP_1. The thyristors are controlled by a phase-shifting RC network of capacitor C_8 and variable resistor R_{29}.

When the switch Π_2 is turned clockwise, the primary winding of transformer TP_2 is directly connected to the AC line (220 V) and the station is operated manually. When the IKS station is used as a conventional cathode station, the output voltage is within 10-15 V.

When the switch Π_2 is in the counter clockwise position, the voltage feeding the thyristor control electrode circuit flows only when the relay $1P_4$ contacts are closed. The winding of this relay is the collector load of transistor T_4, which function together with the transistor T_5 in the time delay circuit. The relay is turned on through a

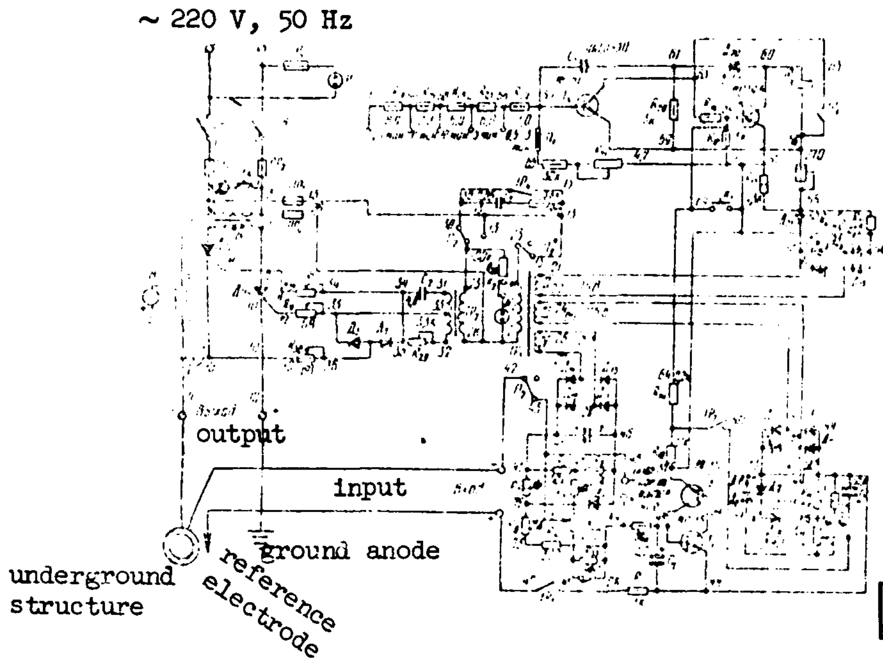


Figure 41. Principal schematic diagram of the pulse cathode station type IKS-AKKh.

metering circuit with transistors T_1 and T_2 (n-p-n and p-n-p).

These transistors are connected to the thyristor circuit. Both transistors of the triggering device are non-conducting in the starting position and only a small current (about 1 μA) flows through their common junction. When a control circuit signal of the proper polarity reaches the base of one of the transistors (T_1 or T_2), they conduct in sequence (each in its own direction) and the system T_1-T_2 latches. This condition can be changed by turning off the current line, by changing polarity, or by decreasing the supply voltage to a level at which the circuit unlatches. Current in the output circuit actually is limited only by the value of the load resistance when transistor T_1 and T_2 are saturated.

According to experimental studies the value of the control voltage does not exceed 400 mV and is sufficiently constant for different types of low power silicon transistors with very small reverse collector current. Since the control voltage of the transistors under consideration is 15-20

times lower than in the low-power transistors, the trigger point of the T_1-T_2 circuit can be easily moved in any direction with a small auxiliary DC source.

The source of the stabilized reference voltage which receives the current from the winding IV of TP_3 transformer is used in the control circuit of the IKS station. The rectifier is a bridge consisting of four germanium diodes D2E (D_{12}-D_{15}). The rectified voltage is stabilized by the silicon stabistor D808 (D_1) and a copper resistor R_6. This resistor provides the necessary compensation for the voltage change in D_1 when the temperature of the surrounding air changes. The reference voltage is measured at resistor R_9, which is connected in series with the resistor R_{33}. There is also a toggle switch BK for reference voltage changes between 1.5-4 V. The reference voltage range makes it possible to change the trigger threshold of the input device between 0-3 V . Figure 42 shows changes of the input device trigger threshold as a function of the reference voltage.

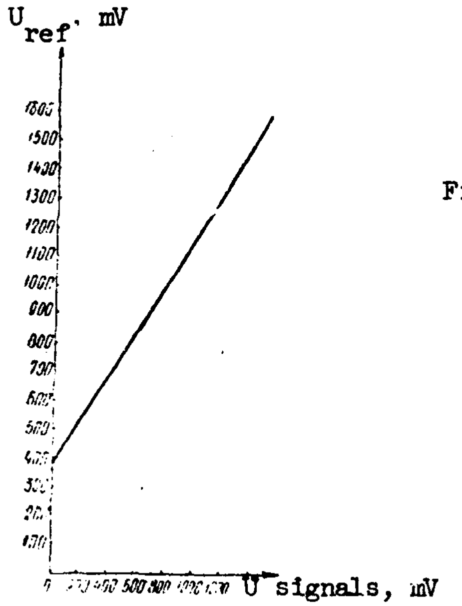


Figure 42. Reference voltage as a function of signals received at the input of the cathode station type IKS-AKKh.

Transistors T_1 and T_2 are supplied with current from a bridge rectifier consisting of four D226 diodes (D_4-D_7) which are connected to winding III of transformer TP_3. Two silicon stabistors D_8 and D_{11} (D808 and D813) stabilize the rectified voltage. The best operation conditions for the

T_1 - T_2 stage is set by the adjustment of the variable load resistor R_{13} which is connected between stabilizing resistors R_{12} and R_{14}. This circuit uses the difference voltage between the nominal stabilization voltages of diodes D813 and D808 (of order of 4 V). Automatic thermal compensation with stabistors D813 is provided to improve the temperature characteristic of the IKS station. These stabistors are connected in the forward direction in series with diodes D_{11} (D_9 and D_{10}). In this the thermal characteristics of the p-n junctions connected in forward direction match with those of the same junctions connected in opposite direction. It is advisable to select stabistors D808 and D813 with close absolute values of temperature coefficients before assembly of the station. The total temperature coefficient in this case will be almost zero.

The time delay circuit is designed with transistors T_3 - T_4 and is a nonsymmetrical multivibrator. Transistor T_4 is conducting in the starting position and the electromagnetic relay 1P (RES-22) is excited. The current passing in 1P keeps the armature in, the holding contact is closed and capacitor C_6 is charged to a full voltage at the winding of the 1P relay.

The operating condition of T_3 is determined by the resistance of R_{21} - R_{22-26} which together with capacitor C_6 constitute the time constant of the transistorized time delay.

Transistor T_4 becomes nonconducting and the 1P relay current is interrupted when the starting button K_1 is closed or when a positive potential from the measuring circuit output is supplied to the base of T_4. The holding contacts of $1P_1$ closes, the contact $1P_2$ breaks the supply line of the measuring circuit and the contact $1P_3$ disconnects the input signal circuit. At the same time the supply line of the phase-shifting device, which is used to control thyristors ДУ$_1$ and ДУ$_2$, is closed by contacts $1P_4$ and the control electrodes receive voltage which fire the thyristors.

At the same time transistor T_3 becomes nonconducting because a reverse voltage (from -4.6 to -4.5 V) from capacitor C_6 and resistor R_{20} is supplied to its base-emitter junction. Transistor R_4 remains nonconducting because there is no current in the divider R_{18} - R_{19}.

When the button K_1 is released or the positive potential from the resistor R_{10} at the measuring device output is removed from the base of T_4, the relay remains without current until the capacitor C_6 becomes recharged with a voltage capable of turning on the transistor T_3 through resistors R_{21}

and R_{22-26} - R_{20}. The transistor T_4 conducts together with T_3. At this time voltage appears in the relay 1P winding which flows to the base of T_3 through diode D_{20} and capacitor C_6. This causes a sudden current increase in the circuit, the relay actuates and closes $1P_1$ contact of the holding circuit. The capacitor C_6 becomes charged to the starting voltage through diode D_{20} and the base-emitter junction of T_3. The resistor R_{16}, which is connected in series to the winding of the R_1 relay, limits the current in the collector circuit of transistor T_4. The diode D_{20} does not pass the recharging current of capacitor C_6 which could reach a considerable value in a short delay time and prevent the release of the 1P relay armature.

The delay time is set by the switch Π_1 which commutates resistors R_{22} - T_{26} and by adjusting the resistance of the variable resistor R_{21}. The delay time is from 30 seconds to 20 minutes.

The transistorized time delay is fed from the stabilized rectifier bridge consisting of four D226 diodes (D_{16}- D_{19}) which are connected to the winding III of transformer TP_3. The rectified voltage is stabilized by silicon stabistor D815E (D_{21}) and by resistors R_{15}- R_{17}.

The electromagnetic relay RES-22 has four groups of contacts; its actuating voltage is 6 V at 30 mA, with a hold-in voltage of 3 V and current of 15 mA.

The output voltage of the IKS station can be controlled manually with a special device which remains connected to the station even when the electronic circuit is removed. The output voltage can be controlled between 10-50 V and the IKS station operates as a conventional cathode station. The required voltage is set up by a variable resistor R_{29}.

All modules and subassemblies of the station IKS are checked before a trial run and the switch Π_2 is turned to the position marked "manual". The negative lead (terminal 9) is connected to the protected structure and the positive lead (terminal 10) to the anode grounding. After connecting the station to the supply line of 220 V, 50 Hz with the use of rotary switch ΠB , the button BK is depressed and the presence of voltage in the primary winding of the power transformer TP_1 is indicated by the indicating light. The required current in the protection circuit is established by gradually turning the variable resistor R_{29} (phase).

The IKS-AKKh station can be checked for the pulse operation conditions with a circuit shown in Figure 43.

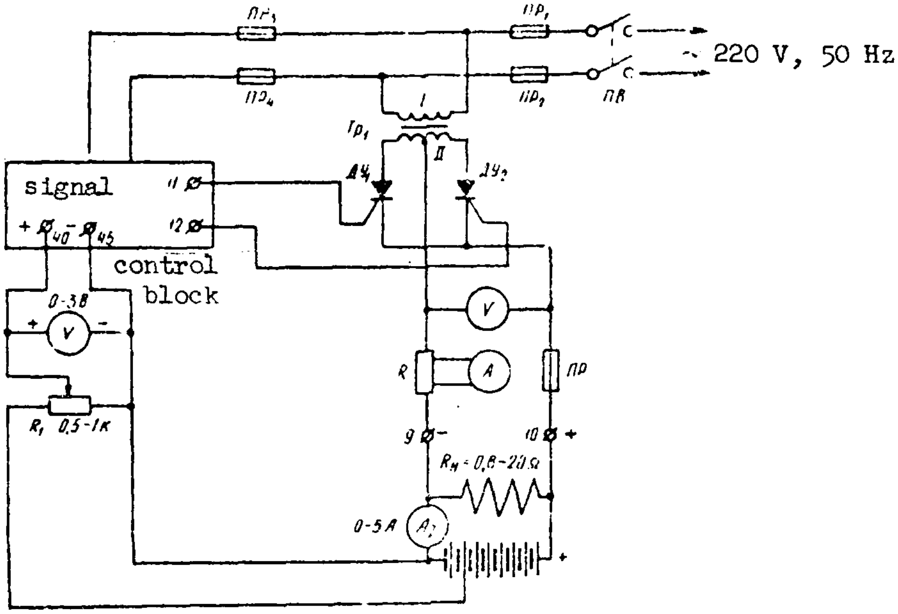


Figure 43. Checking the pulse operation conditions of the cathode station IKS-AKKh.

In place of a signal voltage received from the reference electrode and protected structure, a test signal from a charge-discharge line is connected to terminals 40 and 45 of the control block (after disconnecting the reference voltage and protected structure leads). A battery of 12-15 V connected in parallel with the station output load can be used as the source of the test signal. (The output load can be represented by a cathode protection circuit or a cast iron dummy load resistance of 0.8 - 2 ohms calculated to function at 50 A). Voltage from a battery (or batteries) is supplied to divider R_1 (for example, potentiometer PPZ-11 with 0.5-1 kohm resistance) and to the control circuit with the indicated polarity. A DC voltmeter with a 0-3 V scale is connected in parallel with terminals 40 and 45 to control the signal voltage. An alkaline battery of type 10NKN-10 or 10NKN-22 can be used as the source of the test signal (they are less sensitive to short circuits). The charging current can be measured by a DC ammeter (A_2) with a scale of

0-5 A connected in series with the battery. The station is then turned on (at first by manual control) and operating conditions are established with the variable resistor R_{29}. These conditions should provide the charging current (2 A for NKN-10 and 4 A for NKN-22 batteries). After charging the battery, the positive terminal of the battery is disconnected from terminal 10.

During the next step the switch Π_1 is turned to the position marked "Automatic" and the switch Π_2 to position 1 (minimum delay time of 0.5-3 min) and the resistance of the variable resistor R_1 is reduced to zero (in 30 sec). The signal voltage of 1 V is adjusted at terminals 40 and 45 by the variable resistor R_1 after the station is turned on. The reference voltage at the signal circuit input is gradually decreased by the variable resistor R_9 until the relay 1P is actuated. The toggle switch BK should be set to the position marked "1.5 V" during this procedure and it is advisable to connect a DC voltmeter (0-3 V) to terminals 46 and 49 (marked "reference voltage"). After actuation of the 1P relay the current appears at the station output and in load R_L. The duration of flow of this current will depend on the position of the switch Π_1 and on variable resistor R_{21} which determines the time-setting of the time delay T_3-T_4. If the relay 1P performs properly, the positive polarity of the battery is connected to terminal 10 during a decrease of the reference voltage. At this time the station should operate automatically because the battery, which became charged during the passage of the current through a load R_L, starts to discharge very fast through the small load resistance of 0.5-2 ohm. Voltage at the divider R_1 input and at terminals 40 and 45 also decreases correspondingly and actuates the starting T_1 - T_2 system and also the electronic time delay T_3- T_4. The battery becomes charged again (after the 1P relay was actuated) for a period set by the electronic time delay and discharges through R_L. The DC voltmeter readings should be recorded during this time. When the triggering circuit functions properly, the relay 1P should actuate when the voltage at terminals 40 and 45 drops by 20-25 mV below the established threshold value (1 V, for example).

If the time-delay unit and the triggering circuit function normally, the operation of the station is checked over the complete range of possible signal voltages at different settings of the time-delay unit. After this the auxiliary battery is disconnected, the reference electrode and the protected structure are connected to the control circuit input. The final adjustment of the station is made under actual signal conditions.

CHAPTER 4

SERVICING AUTOMATIC PROTECTION DEVICES OF UNDERGROUND STRUCTURES

Automatic powered draining units and cathode stations do not require any special servicing during operation. However, they should be inspected from time to time. All operation and safety rules for protective units designed for voltages up to 1000 V should be strictly followed.

All protective units can be turned on only when the minus terminal of the power rectifier is connected to the protected structure and the plus terminal is attached to a rail (ground anode in the case of cathode stations).

Units of type UD-AKKh, DUT-AKKh, AKS-AKKh and IKS-AKKh are designed for single phase AC of 220 V, 50 Hz. When the AC supply exceeds 127 V, transformer and autotransformer adapters designed for a load of 2.5-5 KW are used.

It is not recommended to overload draining units above the nominal current. It is best to maintain current in the protective circuit to 70-75% of nominal.

Protection units must not be operated ungrounded. Disconnect the AC supply lines during any inspection of a protection unit, remove fuses and test for the absence of voltage with a control light.

In special cases when it is necessary to inspect the unit without disconnecting the supply line use the following steps: (1) stand on a rubber mat; (2) use only instruments equipped with handles of insulating material; (3) do not touch other objects while inspecting the current-conducting elements (cabinet walls, dividers, pipes, rails, etc.) or persons standing on bare ground; (4) wear overalls, button the sleeves at the wrist, and wear head-gear.

Safety industrial rules should be strictly followed while repairing the operating protection units. It is necessary to log all repairs, examinations and preventive inspections in a log book provided for this purpose.

All external modules located in the cabinet should be inspected once a month. In the case of excessive dirt, modules are removed and the cabinet is cleaned of dirt, dust and water.

All contacts and leads, starting with the reference electrode, should be checked every three months. Clean the contact surface of the

reference electrode lead at the fastening bolt. Inspect at the same time the contact joints of cables to the structure, grounding anodes and rails.

Check at least once a year the tightness of nuts and bolts at the terminals marked "output", "supply line" and "signal", as well as the replacement of thyristors, power diodes and safety fuses. At the same time inspect the condition of soldered joints.

The insulation of the current-conducting parts of the protection units should be inspected once a year with megohmmeter at 500 V.

Check the difference in potentials between a structure and the reference electrode during a regular inspection of protection units. At least once a month check the stability of the protective potential with an automatic recording device of type N-373 or N-39. If the unit does not maintain the required protective potential during the peak load hours of the supply line because of an excessive voltage drop (exceeding 10-15%), make additional adjustments of the control modules considering the maximum voltage drop in the current supply line.

Figure 44 shows the connection diagram of the measuring instruments of the AKS-AKKh unit to adjust the control module when the voltage in the supply line is unstable. The AC line in this case is connected to a voltage regulator (for example, autotransformer of type LATR-1). AC voltmeter V_1 with a scale of 0-240 V is connected in parallel with the supply line input. An equivalent load resistance of o.8-2 ohm is connected to the unit output and the voltage, which is measured by DC voltmeter V_2, is supplied to the divider R_1 (variable resistor of 0.5-2 kohm). The variable resistor R_1 should be connected to an equivalent load R_L in such a way that a voltage of 5 V be applied with a nominal current at the unit output (i.e., R_1 should be connected to 1/10 - 1/20 part of the R_L resistance). If the adjustment is made during operation of the unit with a normally connected cathode protection, an additional voltage divider consisting of two resistors is connected in parallel to terminals 53 and 59. The ratio of resistances should produce the necessary voltage at the ends of R_1 (in the order of 5 V). The voltage from R_1 flows to the signal input of the control module (terminals 60 and 61). The voltage is measured with a DC voltmeter, V_3, having a scale of 0-3 V. The protected structure and reference electrode are disconnected from terminals 60 and 61 during this procedure.

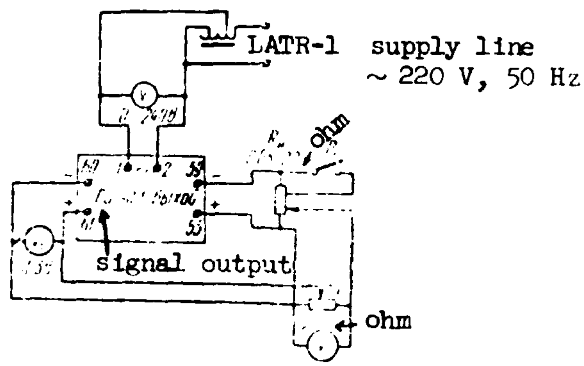


Figure 44. Connecting diagram of instruments to the automatic cathode station type AKS-AKKh when it is necessary to check the protective potential stability in the presence of voltage variations in the supply line.

After adjusting the nominal voltage to 220 V at terminal 1-2 of the AKS-AKKh station with the autotransformer LATR-1, the unit is turned on. The required current at the R_L at a specific signal voltage at the control module input (1 V, for example) is obtained by adjusting the reference voltage (resistor R_4), comparison voltage (resistor R_7) and the signal voltage at the divider R_1. If the voltage at terminals 1 and 2 decreases, the AC voltage of LATR-1 is adjusted until a nominal voltage 220 V is achieved at terminals 1 and 2 (at a given current at R_L and the signal voltage of 1 V).

During the next step the AC voltage supplied to the protection unit is decreased with LATR-1 while watching the readings of voltmeters V_1 and V_3. The DC voltmeter V_3 at the signal input serves as the indicator in this case and checks the voltage stability in the signal circuit (or the potential on the underground structure with respect to ground) when the supply voltage is low. If the unit is adjusted correctly, the variation in the supply line (from +5 to -20%) should not noticeably influence the potential on the structure with respect to ground. The operating characteristics of the unit are set according to local conditions after the boundaries of the current supply line are established by voltmeter V_1 and autotransformer LATR-1. When the voltage drop in the supply line during peak operation hours is excessive,

additional adjustments of the control module of the AKS-AKKh unit are made. The stabilization range of the supply line voltage can be extended by decreasing the reference voltage and increasing the comparison voltage which are applied to the signal circuit of the control block (using variable resistors R_4 and R_7). The input circuit reaction of the control module to variations of the supply line voltage increases because of the increasing comparison voltage with respect to the stabilized reference voltage.

The diagram in Figure 44 can also be used to check the supply line stability of other automatic protection units. It is also suitable for checking the protective potential stability as a function of the load resistance at the unit output (i.e., when the resistance in the supply line varies). For this purpose there is a special knife switch P_1 which can lower the resistance of R_L. The resistance of R_L should decrease in this case 1.5-2 times.

This can be accomplished by setting the nominal voltage at terminals 1 - 2 at 220 V (with autotransformer LATR-1) and the nominal current at R_L corresponding to the operating current of the unit. Then the load resistance R_L is lowered by switch P_1. If the control block of the automatic protection unit functions properly, the voltage at terminals 60 and 61 should decrease for some short time and return to the original value thereafter. The time needed to restore the potentials on terminals 60 and 61 depends on the circuit of the regulating device (in circuits with magnetic amplifiers it is slightly longer than in thyristorized regulators). In many cases it is necessary to protect the control circuits from interference produced by different industrial units. These industrial and high frequency currents could interfere with the performance of automatic circuits and completely disrupt their operation. The presence and nature of interferences can be detected best by an electronic oscilloscope (for example, oscilloscope type C1-1 or smaller sized solid state oscilloscope C1-49 with AC or DC feed lines). The oscilloscope vertical input is connected to the signal input of the control module and the amplitude and frequency of interference in the protective unit control circuit is determined.

The simplest method to protect the control block from interference is to add a shunt condenser (50-200 μf) at the input circuit (Figure 45a). A second conventional (paper) low power capacitor C_2 can be used for protection against audio or high frequency interference. In those cases when the

use of high power capacitors is ineffective or when they interfere with the control circuit functioning, selective LC and RC filters are used. Figure 45b shows one of these filters which consists of a low-frequency choke DP_1 and capacitor C_1 connected in series. The capacitance of C_1 is selected on the basis of the frequency with which the filter will function (100 or 50 Hz). Any suitable filter choke with an inductance of 10-20 h can be used for choke DP_1.

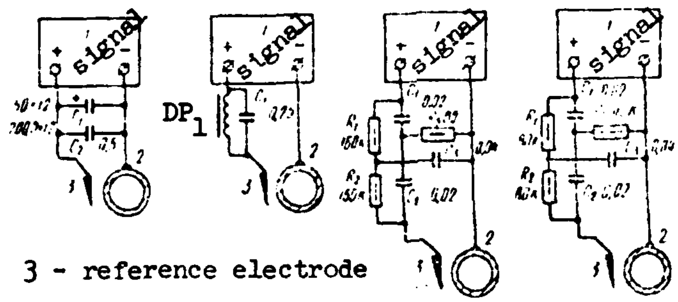


Figure 45. Schematic diagram of input protection filters at the control module of automatic protective devices.

Good results can be obtained with RC filters consisting of two T sections. The dampening characteristic is very high at the cut off frequency (up to 40 dB). At a certain ratio of R and C elements this filter can decrease voltage interference by 60-80 times and only decrease by 20-30% the useful signal voltage.

Filters shown in Figure 45c and 45d were designed for 50 and 100 Hz, respectively. These filters are also effective for frequencies $\pm$20 to 25 Hz. For example, the 50 Hz filter can suppress interference between 30-80 Hz.

Fixed resistors R_1, R_2 and R_3 are used in the circuits of filters (MLT, VS, ULM). Fixed capacitors C_1, C_2 and C_3 should be of type KBG-I, K40P, K40 P-1 or ceramic types KPM or KM. Filters are assembled on small insulated boards enclosed in a metal box for protection against damage. Filters are installed as close as possible to the control block, with shielded output leads.

In the presence of great number of interfering signals, two filters can be connected in series with the signal circuit. For example, when it is

necessary to suppress interference at 50 to 100 Hz, filters shown in Figure 45c and 45d are used in series.

The efficiency of protective units decreases in many instances because of the necessity to limit the current in the protective circuit. This is needed to avoid the harmful effect of harmonics of the rectified current on performance of the railroad signal and electrical control equipment (RSCE). This effect is brought about because the harmonics of the protective current either coincide with the signal current frequency or is very close to it. As a result, relays of the railroad network are subjected to a great extent by the harmonic ripple created by the single-phase full-wave rectifiers from the output load. In order to secure safety for the transportation vehicles it is necessary in many instances to lower the power in the protective circuit thus lower the harmonics at the protective unit output. As a result, the efficiency of anticorrosion devices is decreased.

The use of smoothing filters at the protective unit output is advisable to decrease the ripple component of the rectified voltage.

In the simplest case when it is necessary to slightly lower the effect of the rectified voltage ripple on the performance of the electric circuits of an RSCE, a low-frequency choke DP_1 is connected in series with a load (Figure 46a). This choke, with an inductance of 750-1000 μh, can produce a smoothing coefficient in the order of 5-6 at a nominal current of 300 A. The filter choke core can be made of transformer steel E330-0.35 with a cross-section of 50.5 cm^2. The choke has the following design characteristics: 44 x 208 mm window, 55 x 100 mm stack, 27.8 kg weight. The choke winding consists of 30 turns of copper wire 4 x 25.5 mm^2 in cross section.

A high power capacitor (Figure 46b) connected in parallel with the load provides a much higher smoothing coefficient. Since the capacitance of such a capacitor represents a small resistance for the ripple component of the rectified current, the smoothing coefficient could reach 10-12. The total capacitance of all capacitors, C_1, connected in parallel should be within 20,000 - 28,000 μf (5-7 electrolytic capacitors of type EGTs or K50-3 4000 μf each at 50 V.

The smoothing filter could also be designed as a high series impedance (Figure 45c). It stops the ripple component of the highest amplitude and provides a smoothing coefficient of 8-10. The capacitance

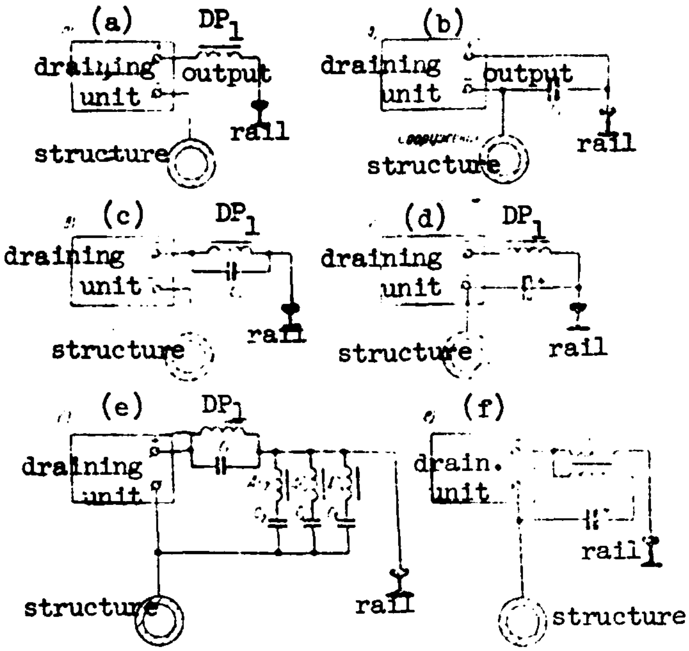


Figure 46. Connection diagram of protective filters

of C_1, which is connected in parallel with the choke DP_1 (Figure 46c), is determined experimentally to produce the maximum suppression of the main harmonic component of the protective current of 100 Hz.

The smoothing effect of the filter can be considerably increased by connecting several resonance shunts in parallel with the load (Figure 46d). The resonance shunt is a capacitance and inductance connected in series. They are selected to make their total impedance to the ripple component to be minimum at a given frequency. Filters DP_2 - C_2, DP_3 - C_3 and DP_4 - C_4 are adjusted to suppress frequencies of 100, 200, and 300 Hz, respectively. The smoothing filter with 2-3 resonance shunts, designed as shown in Figure 46d, can produce the smoothing coefficient of 20-25.

Good results can also be obtained with Γ-shaped filter connected in the protection circuit (Figure 46e). The DP_1 choke inductance should be

in the order of 9-12 μh and the capacitance of C_1 connected in parallel to the load in the order of 10,000-12,000 μf, when the nominal current in the load circuit is 300 A. The capacitance is set by adjusting the filter for the maximum suppression of the ripple component with the frequency of 100 Hz. A correctly adjusted Г-shaped filter provides a smoothing coefficient of 15-20.

A use of an output transformer type filter (Figure 46f) is of advantage for anticorrosion devices. Experimental studies conducted at the Academy of Municipal Economy and at Central Scientific Research Institute of the Ministry of Rail-Road have showed that the protective transformer filter (PTF) is the most effective device for operation in anticorrosion units. The PTF is especially effective in the presence of high values of ripple components originating from the rectifier. The maximum effect produced by this type of filter is due not only to its high smoothing coefficient (in the order of 35-40), but also to its ability to reduce the overall value of inductance and capacitance in the filter circuit.

The PTF consists of capacitor C_1 which is connected at the power rectifier output in series with the primary winding of the transformer TP_1. The secondary winding of TP_1 is connected in series with the load (protection circuit), and its voltage is opposite in phase to the ripple component. Keep it in mind that transformer TP_1 is saturated and its impedance is small. In this case the residual emf of the ripple component in the winding II of TP_1 is very small. Therefore, we can consider the TP_1 as operating under no-load conditions and can disregard losses in its core. Since a load current flows through the winding II of TP_1 and produces directionally constant magnetic flux, an air gap must be provided in the TP_1 magnetic circuit. This gap should be large enough to insure the linearity of the transformer magnetic characteristic at maximum output loads.

The capacitance of C_1 should be sufficient to fully compensate the main harmonic of the rectified voltage. Considering a possible calculation inaccuracy due to idealization of the leakage field in TP_1, an optimum number of turns in the primary winding of TP_1 (20-25%) must be provided during the filter assembly.

The П-shaped core of steel E310-0.35, with 160 x 95 mm window, core cross-section of 130 cm^2 and a 10 mm gap can be used for the construction of the protective transformer type filter for 300 A of load current (total

weight of 80 kg). The primary winding of this filter consists of 40 turns of a wire 5.6 mm^2 in cross-section. Windings can be made of wire type PSD-3.2 (4.13 mm in diameter together with insulation). The secondary winding also consists of 40 turns made of insulated copper wire 95 mm^2 in cross-section. Copper wire 12.5 mm in diameter (M-95, GOST 839-59) can be used for the secondary winding. Four supplementary leads should be provided from taps on the primary winding (36, 34, 30 and 28th windings) for adjusting the filter. The transformer weight is 84 kg with windings.

The voltage drop in the transformer secondary winding does not exceed 1.5 V at 300 A current (its resistance to DC current is 0.0049 ohm). Inductance of the primary transformer winding is 0.0025 h, and of the secondary winding 0.0018 h. The mutual inductance of the primary and secondary windings is 0.0017 h.

Electrolytic capacitors of type K50-3 with a capacitance of 4000 μf at 50 V (6 capacitors) or capacitors of type EGTs with a capacitance of 2000 μf at 50 V (12 capacitors) can be used in this filter.

The correctly adjusted PTF filter can produce a smoothing coefficient of 35-40 for the main harmonic of the rectified current of 100 Hz. It can be used for suppression of harmonic components when the output voltage of the draining unit is 3-24 V. The filter is designed to function at -45 up to +45°C with a relative humidity of 95%. All filter elements are mounted inside of a cabinet equipped with a locking door. The cabinet is installed on a concrete floor with cables along its base, or it could be suspended on a wall (depending on local conditions).

In order to increase the performance reliability of the filter (in the presence of possible overvoltages), the filter capacitors should be protected with a varistor supressor or a neon lamp with an ignition voltage of 50-70 (type MPZ, group "b" or "c", or types MN6 and SN2).

In conclusion, let us consider the step-by-step adjustment of the protection filters (using the PTF filter as an example) capable of suppressing the 100 Hz harmonic. First, the filter input is supplied with an AC voltage of 100 Hz from output of some suitable low-frequency generator (type GZ-18, GZ-33, etc.). A selective voltmeter (type V6-4 or V6-6) should be connected at the filter output. A conventional electronic AC voltmeter (type VK7-3) can be used in place of the selective voltmeter. By changing the

generator frequency and observing the selective voltmeter readings, the actual adjustment of the filter is established (voltage readings should be a minimum). During the next step the number of turns of the transformer primary winding is changed and a new resonant frequency is determined. The voltmeter readings should be minimum. After determining the frequency decrease as a function of the transformer primary winding induction, one or two capacitors are disconnected from the group C_7 (Figure 46f) and the filter frequency adjustment is determined again by the above method. By changing the number of turns in the transformer primary winding in this manner and by adjusting the capacitance of the capacitor block, the resonant frequency of 100 Hz is achieved (according to minimum voltmeter readings).

The final filter adjustment is made directly in the load circuit of the anticorrosion unit, using for this purpose any suitable load resistance of 0.02 ohm (for 300 A current). By changing the current value in the load resistance from 0 to 250-300 A, the value of AC voltage at the filter input and output is measured. The filter smoothing coefficient is determined from

$$K_{sf} = U_{in}\ 100\ \text{Hz}/U_{out}\ 100\ \text{Hz}$$

This coefficient should amount to not less than 30 for the transformer type filter. If it is lower, one additional capacitor is added (2000 and 4000 μf) to the transformer primary winding and an additional adjustment is made.

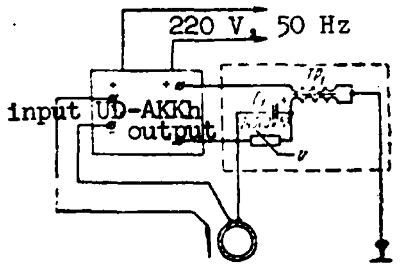


Figure 47. Connection diagram of the protective output filter of type PTF.

Figure 47 shows the connection diagram of the anticorrosion unit with the transformer type filter PTF-150. This filter was designed at the Allunion Red Banner Scientific Research Institute of Rail-Road Transport.

Additional Recommendations for Operation of UD-AKKh Units.

Three variations for the connection of the working windings of the magnetic amplifier YM (Figure 32) are permitted for the automatic UD-AKKh unit.

Variation 1 provides for the connection of all four AC windings in series (two windings in each section connected in series and the sections in series opposition). This variation is used in the presence of large resistance loads (0.08 ohm and higher) and basically when a section of the secondary winding of the power transformer PT_2 is switched into the position marked "12 V".

In variation 2, windings in both sections of YM are also connected in series with each other, but the sections are in parallel opposition). Variation 2 is used with an average value of load resistance (0.03-0.07 ohm). It can also be used for the connection of the secondary winding sections into the "6 V" and "12 V" position (all units come from factory with this type of winding connections of YM).

Variation 3 provides for the parallel connection of two windings in each section and both sections in parallel opposition. This connection is used with a small load resistance (0.02 ohm and lower) and when the sections of the TP_2 winding are in the "6 V" position.

The feedback circuit of YM should be used in the presence of large currents at the unit output. The additional windings of YM in this case are connected to a full-wave rectifier designed with rectifiers D_{14} - D_{15} (Figure 30) which receives current from the TP_2 secondary winding. The feedback windings of YM are connected to make the magnetic flux the same direction as that of the control windings 1 . This type of connection provides an additional magnetization of the core and a higher output voltage because the reactive resistance of YM windings decrease. Therefore it is advantageous to use the feedback circuit when it is necessary to provide a maximum output current of the unit at low values of the load resistance. It was proved in practice that the feedback circuit can be engaged only when the working current exceeds 150 A.

The need to use the feedback circuit of YM can be best determined during a trial run of the anticorrosion unit with the protected structure. The engagement of the feedback circuit increases the current of the unit under no-load conditions and raises the lower threshold value of the regulated

current. Measurements carried out at one of the protected structures showed that current in the load changed from 60 to 172 A (depending on the signal at control input) when the feedback circuit was connected and when the load resistance was 0.03 ohm. In other words, a decrease in the current could amount to only 60 A.

A small additional resistance (1-10 ohm) connected in series with the windings of the feedback can be used for an additional adjustment of the feedback circuit of YM. A small wire rheostat for currents up to 10 A could produce better results in this case. The rheostat should be connected in series to switch B_2 and the resistance value in the feedback circuit should be adjusted until the most advantageous condition for its operation is established. The rheostat is disconnected after adjustment and replaced with a wire resistor of the same value after the optimum value of the additional resistance is measured with ohmmeter.

CHAPTER 5

TECHNOLOGICAL AND ECONOMICAL EFFECTIVENESS OF THE APPLICATION OF AUTOMATIC PROTECTIVE DEVICES

Research carried out at the Academy of Municipal Economy, Institute of Construction of Pipelines, and at Central Scientific Research Communication Institute resulted in a series of anticorrosion devices which include practically all draining and cathode units designed for the protection of main transportation and communication lines in cities.

The automatic draining and cathode units manufactured presently satisfy basically all requirements put forward to devices using normal power supply sources, with the exception of few parameters. Improvements of the existing devices are directed mainly to increase their output voltage.

Analysis of the performance of the majority of cathode protection stations showed that their maximum external resistance is between 0.8-1 ohm. Therefore, it was decided to consider 1 ohm of external resistance as basic for automatic and non-automatic cathode stations. However, the cathode stations which are in serial production are designed for an anode grounding resistance of 0.5 ohm under nominal operation conditions. This results in an irrational use of power by the majority of cathode station. Analysis of 120 cathode stations of type SKZ-AKKh has shown that their capacity was used by 30% only in two cases and only by 20% in the remaining cases. Similar performance was observed among KSS-600 and KSS-120 stations. Consequently, an increase in the output voltage of cathode stations is one of the principal approaches to improve their effectiveness. All power-line cathode stations planned for 1972 should have the voltage limitation within 48/96 V.

All automatic cathode stations, which are classified as power-line stations, and anticorrosion draining units for underground structures are designed to change the potential on underground structures with respect to a reference electrode placed in the surrounding ground.

The application effectiveness of automatic cathode stations can be determined by analyzing the variation of potentials on underground structures in the absence of automatic protection. The variable value of potentials is characterized by an average potential deviation from a given set value.

This deviation can be determined graphically within a positive or negative diagram region showing instantaneous changes of potentials with respect to an average daily value.

Taking into consideration that automatic cathode stations cost 20-30% more than non-automatic stations, it can be said that all expenditures for automatic cathode stations of 600 W can be recovered in 4-5 years when the average hourly deviation of potentials from the average daily deviations would amount to 15%. With increasing power of the cathode stations, as well as in the presence of large potential variations, the expenses could be recovered in a much shorter time.

Parameters of automatic cathode and draining units should correspond to data given in Table 12, depending on the type of units.

Table 12. Parameters of draining units

Name of unit	Output parameters		
	Power, kW	Current, A	Voltage, V
Supply-line and automatic cathode stations	0.6	12.5/25	48/24
	1.2	25/50	48/24
	2	21/42	96/48
	3	31/62	96/48
	5	52/104	96/48
Automatic powered draining units	0.6	50/100	12/6
	1.2	100/200	12/6
	2	165/330	12/6
	3	250/500	12/6

All automatic and draining units should operate normally from a single phase AC line of 220 or 380 V, 50 Hz frequency in the presence of a $\pm 10\%$ voltage deviation. They should operate at temperatures ranging from -45 to +45°C with 95% humidity.

The value of impressed potential produced by an automatic draining unit or by a cathode station should be controlled within 0.8-2.5 V. An

average deviation of the potential from a set value within any 10 minutes interval should not exceed ± 50 mV in the temperature range of +40 to -25°C.

At -25°C the deviation could amount to 5 mV per 10°C. According to the Committee recommendations on protection against corrosion of SEV the input resistance of an automatic protection unit should be not less than 80 kohm. The time constant of automatic and cathode units should not exceed 0.5 sec. All automatic draining and cathode stations should provide a normal operation at a nominal current in the presence of a load resistance of 0.5 R_{nom} and a nominal voltage at a load resistance of 5 R_{nom}. All units should be equipped with proper filters to eliminate radio and television interference. Of importance is a new requirement toward powered units: They should not interfere with a normal functioning of the railroad signaling and control equipment. Therefore, the value of the harmonic component of 50 and 100 Hz rectified current should be within 0.4 and 1 V, respectively. Automatic cathode stations and draining units can be switched to manual control. All basic elements of automatic units (rectifiers, amplifiers, control devices, etc.) should be assembled in modules that could be easily replaced when needed. Cabinets containing draining units and cathode stations of 2 kW and higher should be mounted on a concrete base, with all cables coming from below. Units of less than 2 kW can be mounted either on a concrete base, or hung on a vertical wall of reinforced concrete block. Special terminals should be used for power lines and cables which could provide a speedy disconnection of the units during inspection.

It was proved experimentally that draining units and automatic powered units should be designed to withstand up to 300 V DC reverse voltage.

The main aim of the automatic protective units is to extend the useful life of underground metal structures. It is impossible to determine the useful life of underground structures provided with automatic protection against corrosion and of the economic effectiveness of this protection. We do not have enough actual data accumulated to date. We can analyze only the economic effectiveness of automatic protective units according to those features which could be judged quantitatively.

As opposed to non-automatic draining units adjusted to a maximum draining current which is necessary for producing the protective potential at a peak load time of the rail network, the automatic draining units provide

this protective potential with a current which changes as a function of the traction load. As a result the average draining current could be much lower. The use of a lesser amount of the draining current while the length of the protected zone on underground structure remains unchanged improves the functioning conditions of insulation coatings, decreases harmful effect of stray currents on neighboring structures and lowers the consumption of electrical energy for the protection.

Automation of powered draining units makes it possible to decrease the stray currents from rails. This applies to both the conventionally powered and polarized draining units. This is of importance in the presence of intensive corrosion of rails and of other structures in contact with rails. The average current value decreases noticeably when the protective potential is maintained automatically.

With the use of powered draining units, the protective potential on underground structures stabilizes not only at the point of draining but also at a considerable distance from it. As a result the protective potential at the connecting point of the draining unit, as well as at the protected boundary zone, decreases. In other words, it provides protection of the same area with a lower power draining current.

The annual economy of electrical energy amounts to 3800-4200 watt-hours per one automatic unit, according to our calculations.

The application area of cathode stations has broadened markedly lately, if we consider that a few years ago they were used only for the protection of pipelines and communication cables located outside stray current zones from soil corrosion. As a part of an elaborate anticorrosion protection effort the cathode stations are installed within stray current zones where the polarizing units do not produce the desired effects.

There are cases when it is impossible to connect electrodraining units to rail-road rails because it would interfere with the safe operation of the signaling and control equipment of the railroads. (Draining units can be connected only through two chokes to the third rail). It should also be kept in mind that cathode stations protecting against soil corrosion operate with slow changes of the output parameters and require monthly readjustment. According to data collected by many authors 2 on the operation of cathode stations, the current in these stations can be changed arbitrarily within

200-300%. The average current deviation of the cathode protection in the zone of stray currents could amount to 70-100% from the established level.

The negative effect produced by an excessive negative potential and by the current associated with it based on economical factors in the case of the cathodic protection is aggravated by an excessive consumption of grounding anodes as compared with powered draining units.

Experience with existing cathode stations showed that expenditures for their automation can be recovered within 2-3 years by reducing the electrical energy consumption alone. If other factors are taken into consideration, such as a decrease in operation expenses, the introduction of automatic cathode stations on a wide scale could bring many advantages. Furthermore, the automatic operation of cathode stations prolongs the life of ground anodes because less current will be flowing through them to ground, as compared with non-automatic operation.

TROUBLESHOOTING CHART

Symptoms	Probable Cause	Corrective Action
	Draining Unit UD-AKKh	
Voltage is absent at the power amplifier output when the unit is turned on.	Incorrectly installed or burned out fuses П_2 and П_3.	Check fuses and their contacts; replace fuses if defective.
Signal lights ЛС and ЛО do not light	Defective signal lights.	Check lights and if defective replace them.
Current is present at the power rectifier output but no current in the draining circuit.	1. Defective low voltage fuse П_5.	Check contacts of П_5 and replace the fuse if defective.
	2. Defective ammeter A or the lead from the shunt РШ to ammeter.	Check the rectified current in the draining circuit by connecting the shunt to checking device; check the wiring; repair or replace defective ammeter.
Fuses burn out when the unit is turned on.	1. Unit is overloaded.	Check the current in the draining circuit and readjust the protection circuit.
	2. Short circuit in windings of the power transformer TP.	Disconnect the secondary winding of the transformer TP from D_8-D_{13} rectifiers and check the transformer under no-load conditions.
	3. Breakdown of D_8-D_{13} rectifiers.	Check rectifiers D_8-D_{13} with ohmmeter for forward and reverse conductance and

Symptoms	Probable Cause	Corrective Action
Current in the draining circuit is close to nominal and does not change with time; when the toggle switch is turned on and off the current remains constant in the draining circuit.	1. Defective Π_1 fuse in supply line of the control block.	Check Π_1 fuse and replace it if defective.
	2. Defective transistorized amplifier.	Change the adjustment of transistorized amplifier by rotating the knobs of variable resistors R_1 and R_6. If the potential on the structure remains unchanged, check the voltage at output of rectifiers D_3-D_6 (8 V) and D_6-D_2 (5 V); replace defective power transformer TP_1 or D_1-D_6 rectifiers. If the supply line of the transistorized amplifier is defective, check all amplifier components stage by stage and replace if defective.
Current in the draining circuit is at maximum and does not change with time but drops almost to zero when the toggle switch B_1 is turned on.	The difference in potentials between pipeline and ground does not reach the control block input.	Check the current at the transistorized amplifier input with DC voltmeter. If voltage is absent, check contacts and wiring from the pipeline and reference electrode to the control block input and eliminate defects.

Symptoms	Probable Cause	Corrective Action
No current at the power modules output and also in the draining circuit when the draining unit is turned on.	1. Incorrectly fixed or burnt out fuses ΠP_2 and ΠP_3.	Check fuses and their contacts; replace if defective.
	2. Break or poor contacts in the AC feed line.	Check the voltage at the input of fuses ΠP_2 and ΠP_3; examine the power line and eliminate defects in it.
	3. Defective fuse ΠP_5 at the control block.	Check the fuse ΠP_5 and replace if defective.
Illumination light ЛО or signal light ЛС do not light.	Defective lights.	Check and replace lights if defective.
Despite the presence of voltage at the power rectifier output, the current in the draining circuit is zero.	1. Defective low-voltage fuse ΠP_4.	Check the fuse ΠP_4 and replace if defective.
	2. Defective ammeter A or the line leading to ammeter from the shunt РШ	Check the rectified current in the draining circuit by connecting another ammeter to the shunt РШ ; replace the wiring and ammeter if defective.
Voltage can not be regulated. Voltage in the primary winding of TP_3 is absent but present in the TP_1.	One of the units in the control modules is defective.	Check all units of the control module and and replace defective parts.

Symptoms	Probable Cause	Corrective Action
Current at the unit output can be regulated but the current used by the unit circuit exceeds 20 A.	Break in the circuit of one of the control electrodes of thyristors $ДУ_1$ and $ДУ_2$.	Check circuits of the control electrodes of $ДУ_1$ and $ДУ_2$ thyristors and eliminate defects.
Fuses $ПР_2$, $ПР_3$ and $ПР_4$ burn out when the unit is turned on.	1. Overloading.	Check current in the draining circuit and readjust the unit (using, for example, the limiter $П_1$-R_{36}).
	2. Short circuit in windings of the power transformer TP_3.	Check the transformer operation by disconnecting the TP_3 secondary winding from rectifiers DC_1-DC_6. If there is a short circuit between windings of TP_3 and between windings and the transformer c e, replace the transformer or repair it if possible.
	3. Breakdown of power rectifiers DC_1-DC_6.	Check rectifiers DC_1-DC_6 with an ohmmeter for forward and reverse conductivity and if defective replace the rectifiers.

Symptoms	Probable Cause	Corrective Action
No current in the draining circuit when the toggle switch TB_1 is turned on and off. When the button KC is pressed the bulb ЛС lights.	1. Bias adjustment or feed line break of the reference voltage (rectifiers D_1-D_4).	Adjust the variable resistor R_4 with a knob.
	2. One of the units in the control block defective.	Check the voltage at terminals 31-33 and eliminate defects. Check all units stage by stage in the control module, starting with rectifiers, pulse block and УПТ.
Current in the draining circuit is almost at maximum and does not change with time; current does not change when the toggle switch TB_1 is turned on.	Difference in potentials between the structure and reference electrode does not reach the control input.	Check the signal voltage at the control block input with a DC voltmeter. If the signal is absent, check contacts and lines from the structure and reference electrode to the control block input and eliminate defects.
	Cathode Station AKS-AKKh	
Current is absent at the power rectifier output when the station is turned on; ammeter does not show any readings.	1. Incorrectly fixed or burned out fuses ΠP_1 and ΠP_2.	Check contacts and condition of ΠP_1 and ΠP_2 fuses, replace if defective.
	2. Defective rotary switch П B in the supply line.	Check the rotary switch П B and repair or replace if defective.
	3. Break in the supply line or poor contacts.	Check the voltage at the input terminals with a control lamp as well as the condition of the

Symptoms	Probable Cause	Corrective Action
		supply line and eliminate defects.
Signal lights ЛС$_1$ and ЛС$_2$, or lamp ЛО does not light.	1. Defective fuses ПР$_3$-ПР$_4$ (ЛС$_1$ and ЛС$_2$) and the push-button switch ВК (ЛО).	Check the contacts, condition of fuses and the push-button switch ВК and replace defective fuses and ВК switch.
	2. Defective signal lights ЛС$_1$ and ЛС$_2$ as well as light ЛО.	Check light ЛС$_1$, ЛС$_2$ and ЛО and replace if defective.
DC voltmeter does not register but there is a current in the protective circuit.	DC voltmeter is defective or wiring to it is damaged.	Check the voltmeter and replace if defective; check the condition of wiring and eliminate defects.
Despite the presence of voltage at the station output, the current in the cathodic protection circuit is zero.	1. Defective low-voltage fuse ПР$_5$.	Check contacts and the condition of the fuse ПР$_5$; replace it if defective.
	2. Defective DC ammeter or break in the line between the shunt РШ and ammeter.	Check the current in the cathodic protective circuit by connecting it directly to the shunt РШ.
Fuses ПР$_1$, ПР$_2$ and ПР$_5$ burn out when the station is turned on.	1. Overloading.	Check the operation of the cathode station at a decreased output voltage (by the variable resistor R_{14}, "phase" position).

Symptoms	Probable Cause	Corrective Action
	2. Breakdown of rectifiers D_{25}, D_{28} or thyristors D_{25}, D_{28}.	Check rectifiers D_{27} and D_{28} for forward and reverse conductivity as well as of thyristors D_{25} and D_{26} for breakdown with an ohmmeter; replace if defective.
	3. Short circuit in the power rectifier output to the station cabinet.	Check insulation between the station frame and the rectifier D_{25}-D_{28} output; eliminate defects.
	4. Short circuit between windings of the power transformer TP_3.	Check the transformer TP_3 operation under no-load conditions by disconnecting first the secondary transformer windings and check the current in the primary winding. Eliminate short circuit between the transformer windings or between windings and the transformer case, or replace the transformer.
Neither current nor voltage are present in the cathodic protection circuit and the output current and voltage cannot be adjusted by the variable resistor R_{14}.	1. Incorrectly connected switch T П-2 at the phase controlling block.	Switch the tumbler into the outmost position and adjust the current in the protective circuit by the variable resistor R_{14}.
	2. Defective tumbler switch TП 1-2 or the power transformer TP_2.	Check and replace the tumbler if defective; check the presence of

Symptoms	Probable Cause	Corrective Action
		voltage in B_2TP_2 winding and eliminate defects or replace the power transformer TP_2.
	3. Damaged wire-wound variable resistor R_{14}, breakdown of D_{23}, D_{24} diodes. Open R_{15}-R_{17} resistors.	Check all components of the phase controlling module and replace defective parts.
Current disappears in the cathodic protection circuit when the station is switched from manual to automatic operation.	1. Incorrectly set phase switch ТП 1-2.	Switch the tumbler ТП1-2 into another outmost position.
	2. Defective switch $П_1$ ("Manual" - "Automatic").	Check and replace if defective switch $П_1$.
	3. Defects in the control windings of УМ.	Check the connecting wiring between the AC windings of УМ and the switch $П_1$ and between the УПТ output and control windings of УМ. Eliminate defects.
	4. Poor contact or discontinuity in operating windings or in control windings.	Check the condition of contacts at output terminals of УМ and of all windings of УМ; repair or replace the УМ.
	5. Defective transistorized УПТ.	Check УПТ stage by stage (starting with the power transformer TP_1); check all rectifiers and check again the УПТ. Replace

Symptoms	Probable Cause	Corrective Action
		defective components and switch on the spare block.
Current in the cathodic protection circuit either is very small or does not change with time when the station is switched to automatic operation.	1. Too large reference voltage.	Adjust variable resistor R_4 setting (position "reference voltage").
	. Very low sensitivity.	Adjust variable resistor R_6 setting (position "sensitivity").
	3. Control signal is small.	Adjust the variable resistor R_{12} setting (position "signal").
	<u>Cathode Station IKS-AKKh</u>	
When the station is turned on there is no voltage at the power rectifier output and the ammeter does not show any readings (station is under manual control).	1. Incorrectly fixed or burned out fuses ΠP_1 and ΠP_2.	Check contacts and condition of fuses ΠP_1 and ΠP_2 and replace if defective.
	2. Defective rotary switch ΠB in the supply line.	Check rotary switch ΠB, repair or replace if defective.
	3. Incorrectly set variable resistor R_{24}.	Adjust the resistance value ("phase").
	4. Power transformer TP_2 windings are connected incorrectly.	Interchange connections of the primary and secondary TP_2 windings (31-32 or 28-29 terminals).
	5. Break or poor contact in the supply line.	Check the voltage at A-B terminals and eliminate defects.

Symptoms	Probable Cause	Corrective Action
Signal light LC_1 does not light when the push-button switch BK is pressed.	Defective BK switch or the light LC_1 is burned out.	Replace defective switch or light.
DC voltmeter does not register but there is current in the protective circuit (according to the panel ammeter).	Defective voltmeter or wiring leading to it.	Disconnect and check the DC voltmeter; replace with another meter; check the voltmeter wiring and eliminate defects.
Despite the presence of voltage at the station output, the current in the protective circuit is zero.	1. Defective low-voltage fuse ΠP_5.	Check the condition and contacts of the fuse ΠP_5 and replace it if defective.
	2. Defective panel voltmeter, or line is broken from the shunt to ammeter.	Check the current in the protective circuit by connecting the checking instrument to the shunt PШ in place of the panel ammeter. When current is present in the protective circuit, check the wiring from the shunt to the ammeter; eliminate defects or replace ammeter.
Fuses ΠP_1 and ΠP_2 burn out when the station is turned on.	1. The station is overloaded.	Check the operation of the station at a lower output current (by adjusting the variable resistor R_{29} ("phase" position).

Symptoms	Probable Cause	Corrective Action
	2. Breakdown of one or both ДУ$_1$ and ДУ$_2$ thyristors.	Check thyristors with an ohmmeter and replace if defective.
	3. Short circuit in the output leads of the thyristor rectifier to the station case.	Check the condition of insulation between the station cabinet and the rectifier ДУ$_1$-ДУ$_2$output and eliminate defects.
	4. Short circuit between windings of the power transformer TP$_1$.	Disconnect the secondary TP$_1$ winding from thyristors ДУ$_1$-ДУ$_2$and check the transformer operation under no-load condition; check current in the primary transformer winding. Eliminate short circuit or replace the transformer.
Voltage is present in the power transformer TP$_1$ primary winding, as well as the voltage at the station output, but there is no current in the cathodic protection circuit and the current and voltage can not be changed by the variable resistor R_{29}.	1. Defective ПР$_3$ and П Р$_4$ fuses.	Check the condition of fuses and their contacts and replace them if defective.
	2. Defective class of operation switch.	Check the П$_2$ switch and replace if defective.
	3. Resistance discontinuity of variable resistors R_{29}, R_{30}, R_{31}, R_{32}, or breakdown of diodes D_2-D_3.	Check all components of the voltage controlling unit of power rectifier and replace if defective.

Symptoms	Probable Cause	Corrective Action
Upon switching from manual to automatic operation, currents disappears in the cathodic protection circuit.	1. Bias adjustment of the reference voltage unit (resistor R_9).	Check the tumbler switch setting (1.5 or 4.5 V) and adjust the variable resistor R_9.
	2. Defective Π_2 switch.	Check the contact terminals of Π_2 and eliminate defects.
	3. Defective T_1-T_2 triggering unit or the electronic time delay T_3-T_4.	Check the components involved stage by stage, starting with D_4-D_7 and D_{16}-D_{19} rectifiers and going to the electromagnetic relay 1P.

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